The π-axion and π-axiverse of Dark QCD

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Copernicus Seminar

Talk Based on:
Alexander, Gilmer, Manton, EM '23. arXiv:2304.11176
Maleknejad & EM PRD '22

Outline

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1. Introduction: Axions past present and future

2. The π-axiverse

3. π-axion DM

4. Experimental Arenas

Introduction

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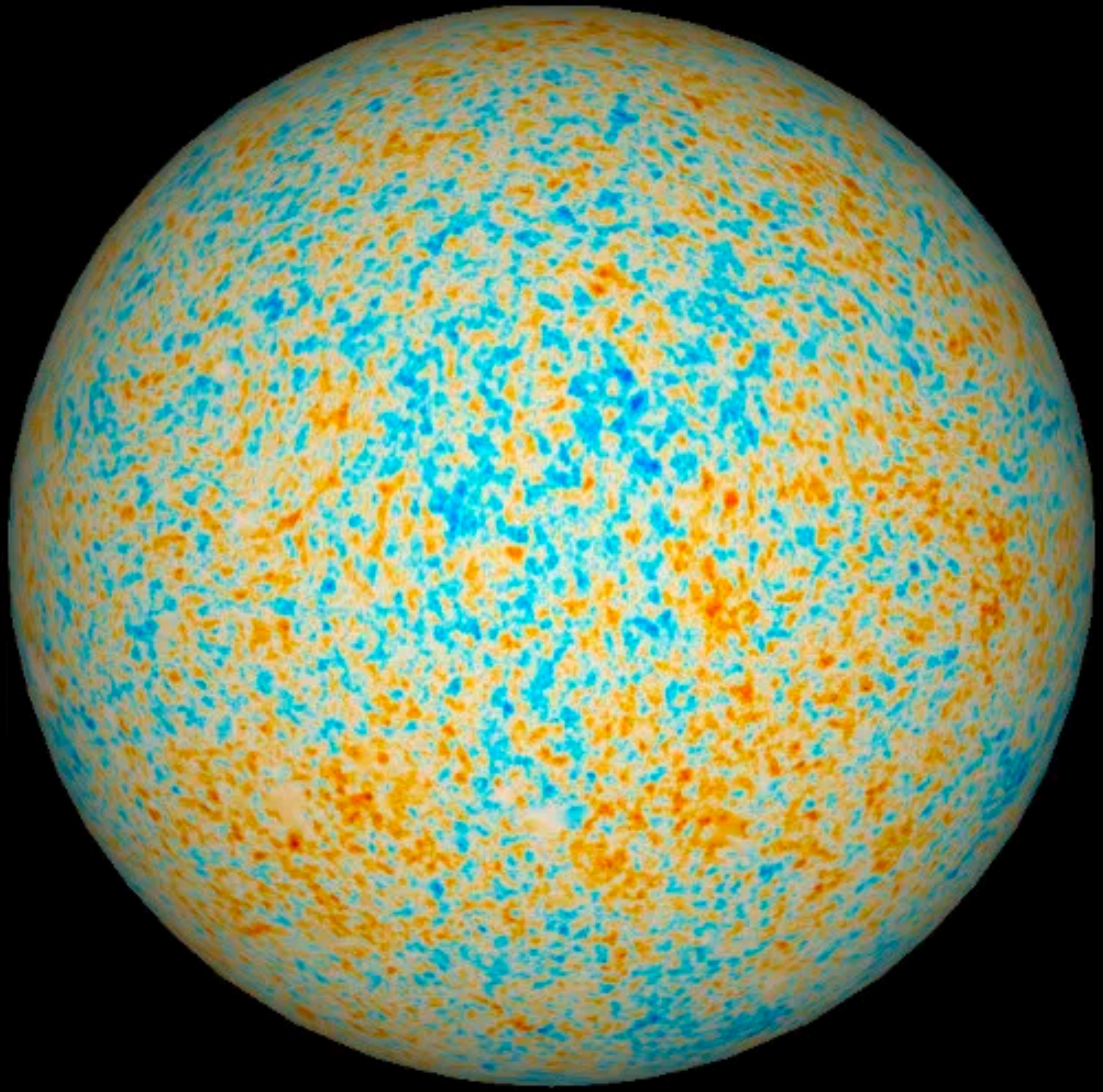
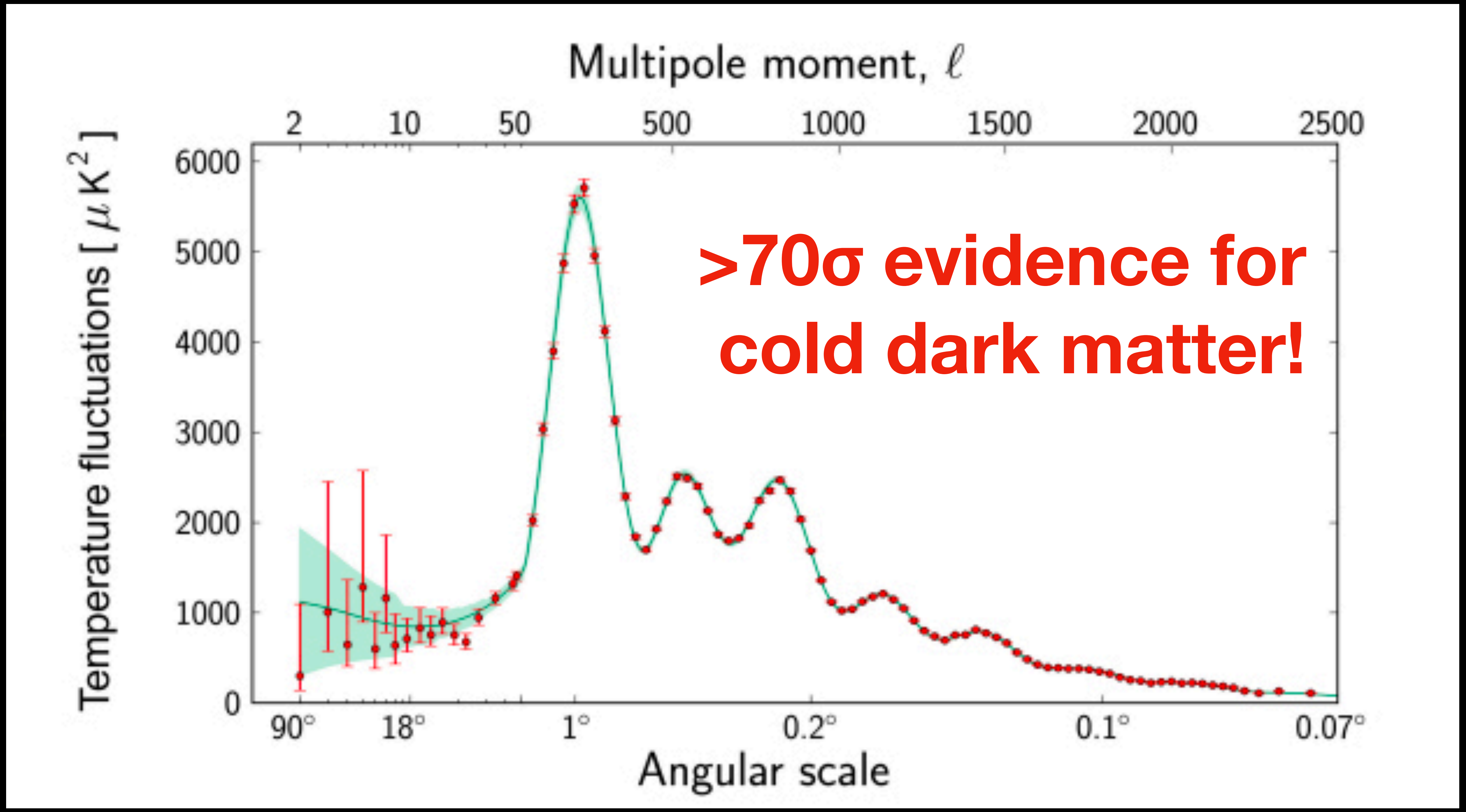
The case for Dark Matter





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Axions circa late 1970's

The Strong CP Problem

$$\mathscr{L} = \frac{g^2}{32\pi^2}\theta G\tilde{G} \qquad \theta < 10^{-10}$$

[PQWW, DFSZ, KSVZ]

$$\mathscr{L}(\Phi \equiv \phi e^{ia/f_a}) = \frac{1}{2}|\partial_\mu \Phi|^2 - \lambda(|\Phi|^2 - f_a^2)^2 - \Lambda^4 \cos(\theta + \frac{a}{f_a}) + \frac{a}{f_a}G\tilde{G}$$

Around the same time: Choi, Kim
Composite (dynamical, colored) axion:

Solve strong CP with:
Dark quarks charged under both dark ("axi-") color and SM color
New heavy quarks; other colored particles

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Axion Dark Matter

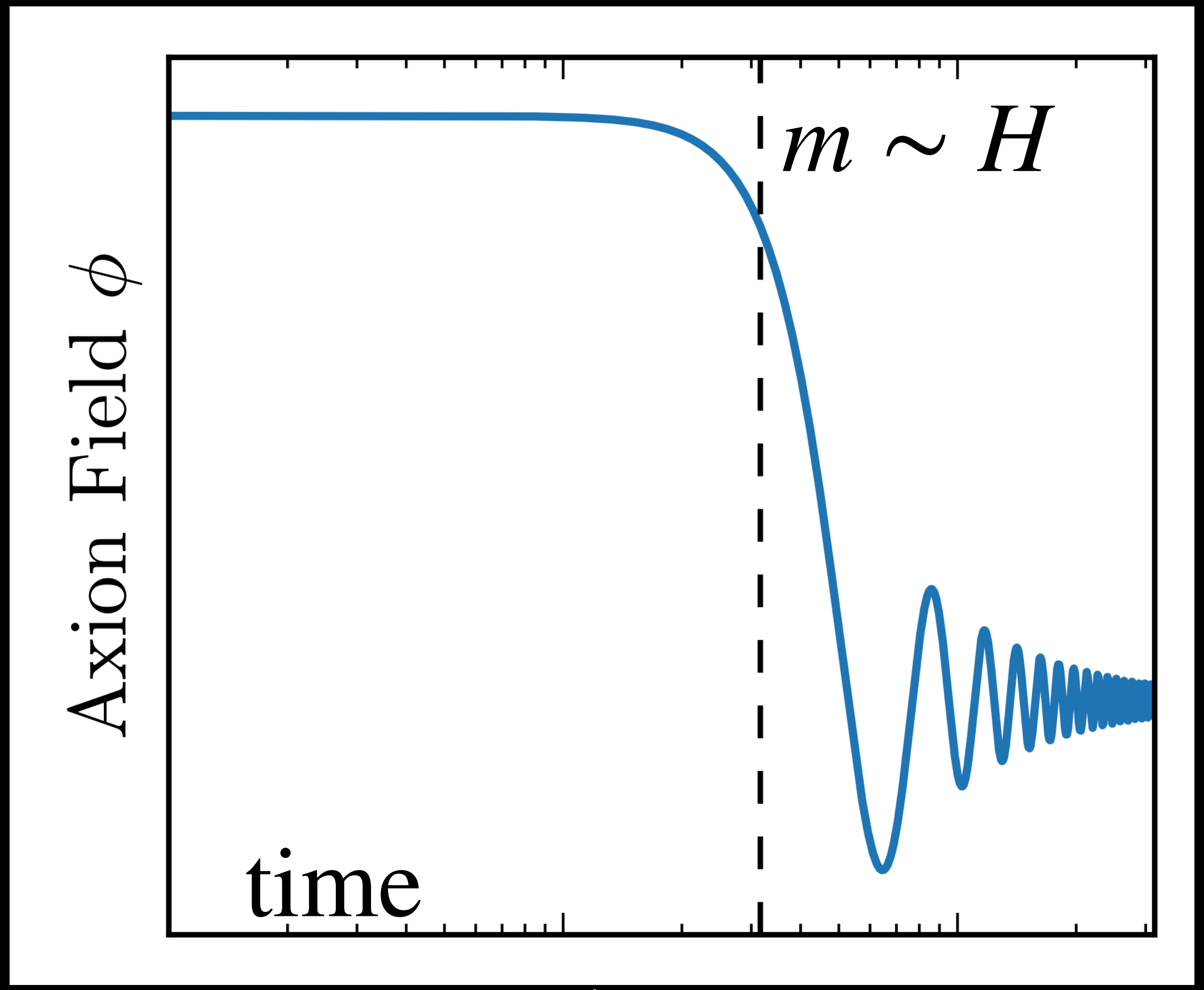
$$\mathscr{L} = |\partial_\mu \Phi|^2 - \lambda(|\Phi|^2 - f^2)^2 - \Lambda^4 \cos(\frac{a}{f_a})$$

ALP: axion-like particle = Goldstone Boson of
Spontaneous breaking of global U(1) symmetry

$$\ddot{a} + 3H\dot{a} + m^2 a = 0 \qquad m \ll \text{eV}$$

**See e.g. Marsh '15
For a review**

$\Omega_{\rm DM}$ set by
initial "misalignment" ϕ_i



Lots of neat particle physics:

$$\mathscr{L}_{\rm int} = \frac{a}{f}\epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma} = \frac{a}{f}E \cdot B$$

Axions (ALPs) from String Theory: The String Axiverse

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Arvanitaki et al ’09
Goodsell, Ringwald ’12

Gauge invariance in 10 dimensions: $B_{\mu\nu} \to B_{\mu\nu} + \partial_{[\mu} f_{\nu]}$

Shift symmetry of scalar in 4 dimensions: $b \to b + c$

Many axions! In type IIB:

Fundamental Axion	4-form axions	2-form axions	
C_0	$\vartheta = \int_{\Sigma^4} C_4$	$c = \int_{\Sigma^2} C_2$	$b = \int_{\Sigma^2} B_2$

Census of the String Axiverse

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For recent review:
Cicoli, Licheri, Mahanta, EM, Pedro, Scalisi '23

Universal axion

$$C_0$$

Huge mass from moduli stabilization:

$$W_0 = \int (F_3 - SH_3) \wedge \Omega$$

$$V(C_0) \sim |W|^2$$

4-form axions:

$$\vartheta = \int_{\Sigma^4} C_4$$

Large mass from mod stab in KKLT or small-cycles of LVS. Only possible cosmological C4 axion: LVS bounding cycle

$$c = \int_{\Sigma^2} C_2$$

Good candidate for cosmology

But can be eaten!
By branes at singularities

2-form axions:

$$b = \int_{\Sigma^2} B_2$$

Shift symmetry broken by DBI action on branes, and perturbatively in Kahler potential

$$K = -3\ln\left(\Re(T) - \frac{2\gamma}{g_s^2} b^2\right).$$

- Mass generated by instantons, gaugino condensation etc. .
- Need 1 non-pert effect per each axion
- Spectrum of non-perturbative effects gives rise to spectrum of periodicities (decay constants) and couplings

From Axion DM to ULDM

Review: Ferreira '20

Alexander, EM, Spergel 2021
Alexander, EM, Spergel 2019
Maleknejad & EM 2022

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ULDM models are their own icebergs

Maleknejad & EM 2022

Correlated signals can discriminate ULDM models

Enter the π-axiverse

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Pions: textbook physics — and a lot like axions!

$$U = \frac{F_\pi + \sigma(x)}{\sqrt{2}} \exp\left(\frac{2i\pi^a(x)\tau_a}{F_\pi}\right) \qquad \mathscr{L} = \frac{F_\pi^2}{4}\mathrm{Tr}[(D_\mu U)(D^\mu U)^\dagger] + \frac{\langle q\bar{q}\rangle}{2}\mathrm{Tr}[MU + M^\dagger U^\dagger] + \ldots.$$

Pion Potential: $V(\pi) \propto \mathrm{Tr}[MU + M^\dagger U^\dagger] \to \cos\left(\frac{\pi}{F_\pi}\right)$ $\quad (M_{ij} = m_\pi \delta_{ij})$

Energy scales: $m_\pi^2 \sim \Lambda m_q \;,\; F_\pi \sim \Lambda$

ALP-DM-like cosmological evolution: $m_{\pi_0} < \mathrm{eV} \;,\; F_\pi \gtrsim 10^{10}\mathrm{GeV}$

$$\Rightarrow m_q < 10^{-19}\mathrm{eV} \;,\; \Lambda \gtrsim 10^{10}\mathrm{GeV}$$

“π-axions”

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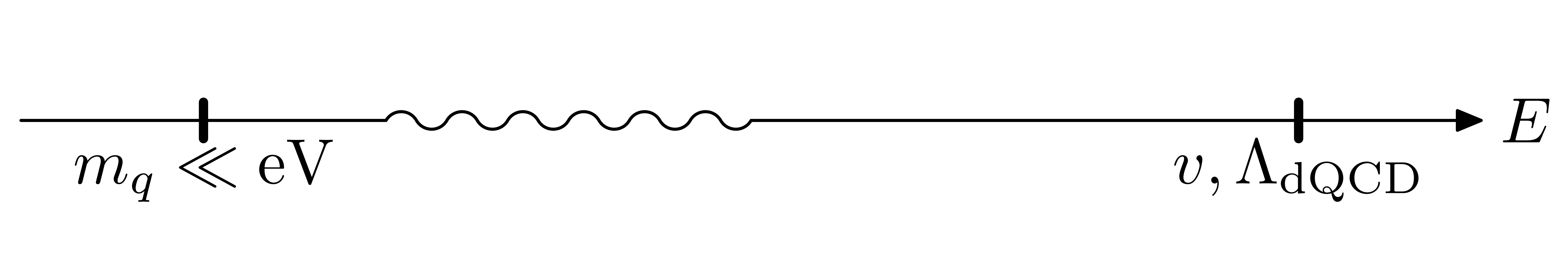
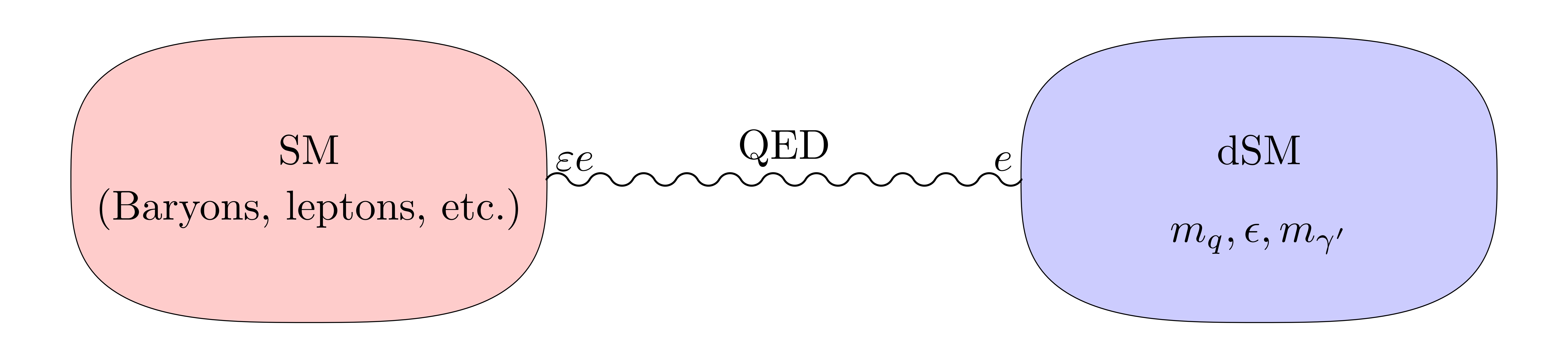
The Dark Standard Model

Key points

1. Two energy scales



2. SM portal: photon kinetic mixing (millicharges)



Dark Pions

$$m_\pi^2 \simeq \frac{\langle q\bar{q}\rangle}{F_\pi^2}\sum_i m_{q_i} \qquad \Delta m^2_{\pi_i^\pm} \simeq \begin{cases} \alpha'_e F_\pi^2 & , \; m_{\gamma'} < F_\pi \\ \alpha_e \varepsilon^2 F_\pi^2 & , \; m_{\gamma'} > F_\pi, \end{cases}$$

Quark masses:

$c_1 m_I$, $c_2 m_I$

$c_3 m_{II}$, $c_4 m_{II}$

$c_5 m_{III}$, $c_6 m_{III}$

Spectrum of π-axions in Dark QCD

π-axion	quark content	mass squared ($m^2_{\pi^i}$)	charge [ε]
5 Real Neutral:			
π_3	$u\bar{u} - d\bar{d}$	$(c_1 + c_2)m_\text{I} F_\pi$	0
π_8	$u\bar{u} + d\bar{d} - 2s\bar{s}$	$((c_1 + c_2)m_\text{I} + c_3 m_\text{II})\, F_\pi$	0
π_{29}	$c\bar{c} - b\bar{b}$	$(c_4 m_\text{II} + c_5 m_\text{III})\, F_\pi$	0
π_{34}	$c\bar{c} + b\bar{b} - 2t\bar{t}$	$(c_4 m_\text{II} + (c_5 + c_6)m_\text{III})\, F_\pi$	0
π_{35}	$-u\bar{u} - d\bar{d} - s\bar{s} + c\bar{c} + b\bar{b} + t\bar{t}$	$((c_1 + c_2)m_\text{I} + (c_3 + c_4)m_\text{II} + (c_5 + c_6)m_\text{III})\, F_\pi$	0
6 Complex Neutral:			
$\pi_6 \pm i\pi_7$	$d\bar{s}/\bar{d}s$	$(c_2 m_\text{I} + c_3 m_\text{II})\, F_\pi$	0
$\pi_9 \pm i\pi_{10}$	$u\bar{c}/\bar{u}c$	$(c_1 m_\text{I} + c_4 m_\text{II})\, F_\pi$	0
$\pi_{17} \pm i\pi_{18}$	$d\bar{b}/\bar{d}b$	$(c_2 m_\text{I} + c_5 m_\text{III})\, F_\pi$	0
$\pi_{19} \pm i\pi_{20}$	$s\bar{b}/\bar{s}b$	$(c_3 m_\text{II} + c_5 m_\text{III})\, F_\pi$	0
$\pi_{21} \pm i\pi_{22}$	$u\bar{t}/\bar{u}t$	$(c_1 m_\text{I} + c_6 m_\text{III})\, F_\pi$	0
$\pi_{30} \pm i\pi_{31}$	$c\bar{t}/\bar{c}t$	$(c_4 m_\text{II} + c_6 m_\text{III})\, F_\pi$	0
9 Charged:			
$\pi_1 \pm i\pi_2$	$u\bar{d}/\bar{u}d$	$(c_1 + c_2)m_\text{I} F_\pi + 2\xi_1(e\varepsilon F_\pi)^2$	± 1
$\pi_4 \pm i\pi_5$	$u\bar{s}/\bar{u}s$	$(c_1 m_\text{I} + c_3 m_\text{II})F_\pi + 2\xi_2(e\varepsilon F_\pi)^2$	± 1
$\pi_{15} \pm i\pi_{16}$	$u\bar{b}/\bar{u}b$	$(c_1 m_\text{I} + c_5 m_\text{III})F_\pi + 2\xi_3(e\varepsilon F_\pi)^2$	± 1
$\pi_{11} \pm i\pi_{12}$	$d\bar{c}/\bar{d}c$	$(c_2 m_\text{I} + c_4 m_\text{III})F_\pi + 2\xi_4(e\varepsilon F_\pi)^2$	∓ 1
$\pi_{23} \pm i\pi_{24}$	$d\bar{t}/\bar{d}t$	$(c_2 m_\text{I} + c_6 m_\text{III})F_\pi + 2\xi_5(e\varepsilon F_\pi)^2$	∓ 1
$\pi_{13} \pm i\pi_{14}$	$s\bar{c}/\bar{s}c$	$(c_3 + c_4)m_\text{II} F_\pi + 2\xi_6(e\varepsilon F_\pi)^2$	∓ 1
$\pi_{25} \pm i\pi_{26}$	$s\bar{t}/\bar{s}t$	$(c_3 m_\text{II} + c_6 m_\text{III})F_\pi + 2\xi_7(e\varepsilon F_\pi)$	∓ 1
$\pi_{27} \pm i\pi_{28}$	$c\bar{b}/\bar{c}b$	$(c_4 m_\text{II} + c_5 m_\text{III})F_\pi + 2\xi_8(e\varepsilon F_\pi)^2$	± 1
$\pi_{32} \pm i\pi_{33}$	$b\bar{t}/\bar{b}t$	$(c_5 + c_6)m_\text{III} F_\pi + 2\xi_9(e\varepsilon F_\pi)^2$	∓ 1

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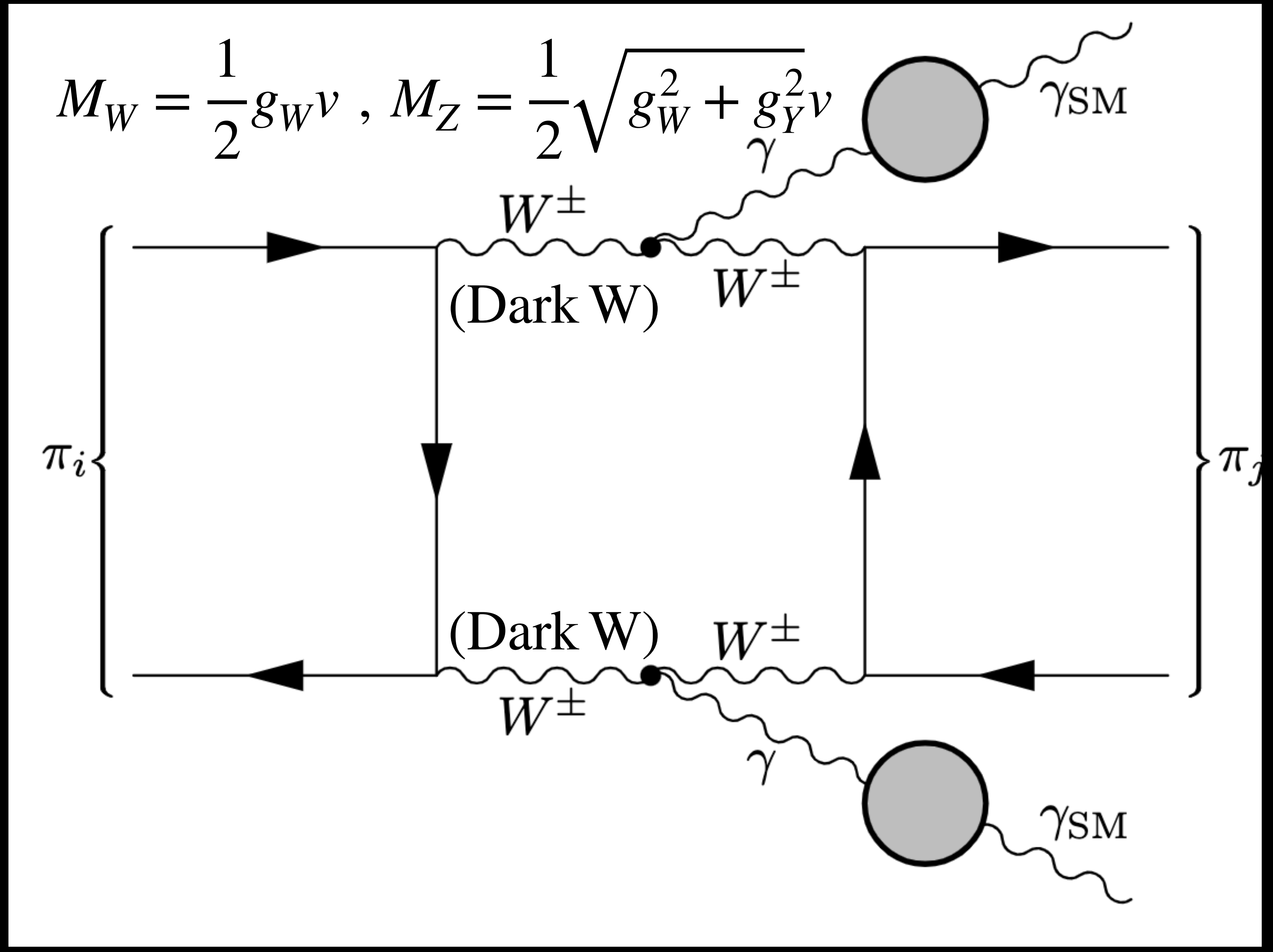
Photon Portal to the SM:

$\varepsilon F_{\mu\nu}\tilde{F}^{\mu\nu} \Rightarrow$ millicharges, π-axion—photon couplings

1. Neutral scalar pion: $\mathscr{L} = \lambda_1 \frac{\varepsilon^2}{F_\pi}\pi^0 F\tilde{F}$
2. Charged pion: $\mathscr{L} \sim \varepsilon^2 \pi^+\pi^- A_\mu A^\mu$
3. Flavor violating:

$$\mathscr{L} = \lambda \frac{\varepsilon^2}{M^2}\pi_i \pi_j^* F_{\mu\nu}F^{\mu\nu} + h.c.$$



π-axion Lifetime:

$$\tau_{\pi^0} \sim H_0^{-1}\left(\frac{F_\pi}{\text{TeV}}\right)^2 \left(\frac{0.3\text{eV}}{m_{\pi^0}}\right)^3 \frac{1}{\varepsilon^4}$$

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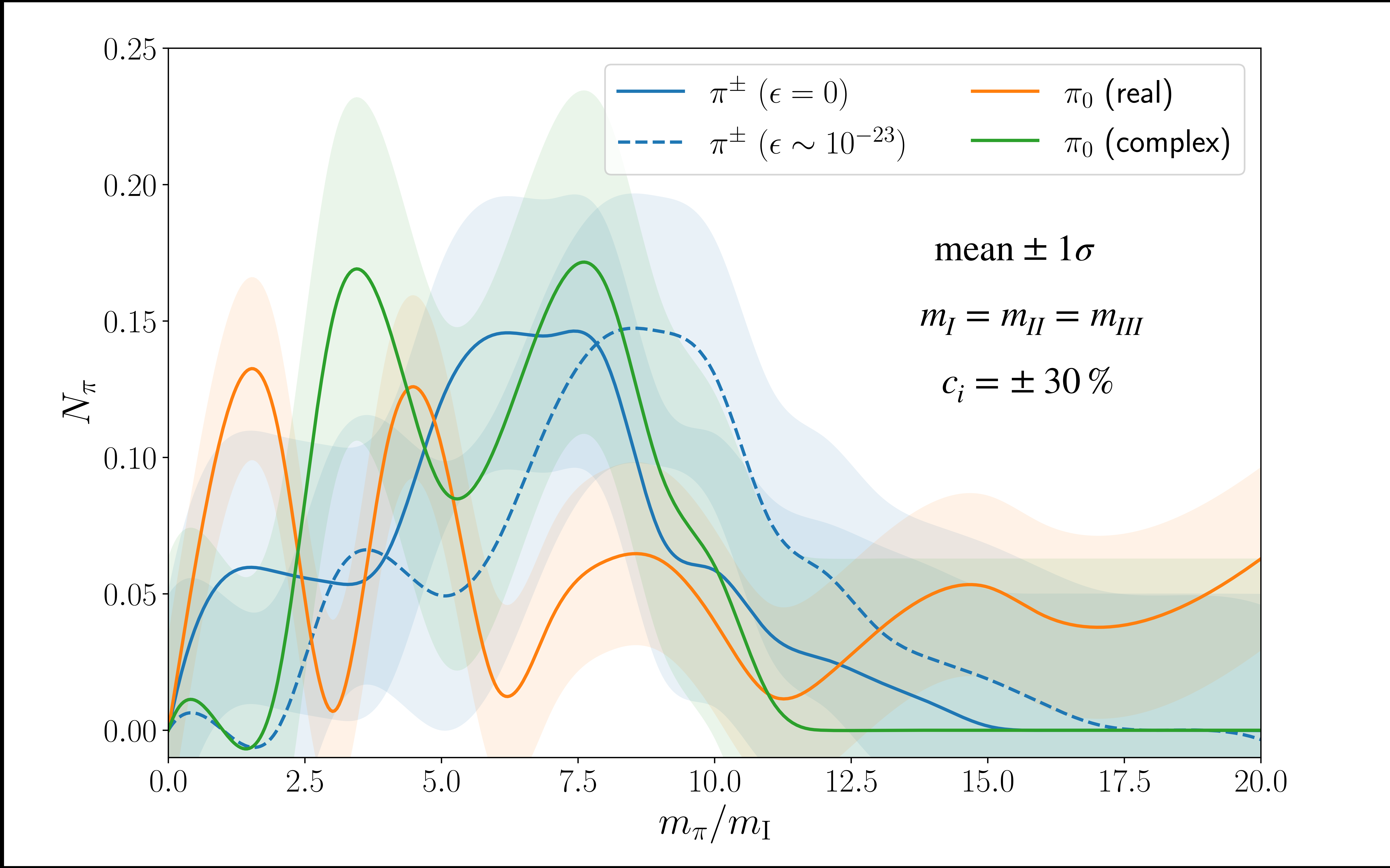
Statistical Distribution of masses



π-axion DM

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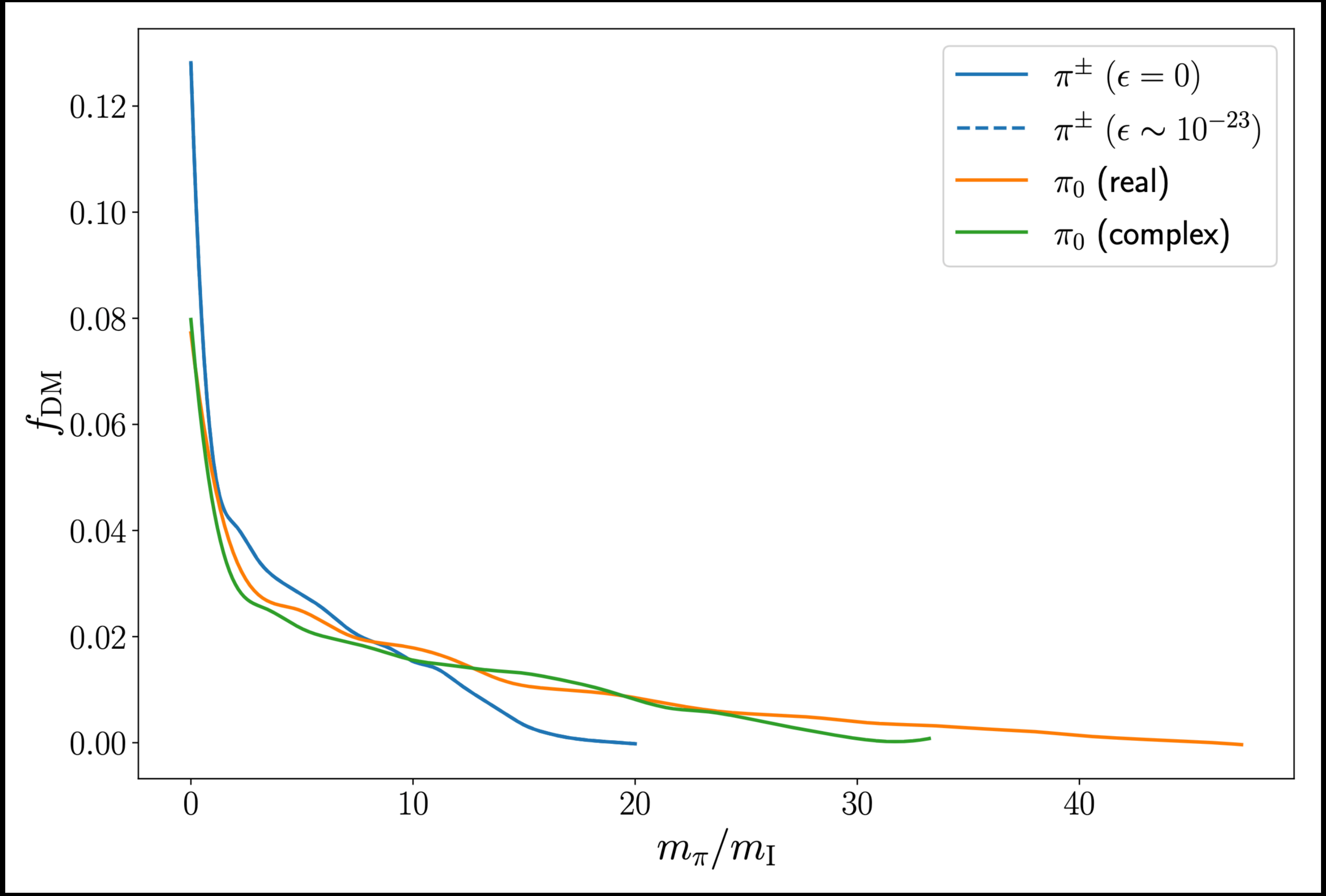
Misalignment Relic Density

- Assume dQCD phase transition before inflation
- CMB Isocurvature: $H_{\rm inf} \lesssim 10^{10}(F_\pi/M_P)\,{\rm GeV}$
- Cosmological stability: $\tau_{\pi^0} \sim H_0^{-1}\left(\frac{F_\pi}{\rm TeV}\right)^2\left(\frac{0.3{\rm eV}}{m_{\pi^0}}\right)^3\frac{1}{\varepsilon^4}$
- Heavy Dark Photon: $m_{\gamma'} > F_\pi$
- Late-time relic density produced by misalignment:

$$\Omega_{\pi_i} = \frac{1}{6}(9\Omega_r)^{\frac{3}{4}}\frac{F_\pi^2}{M_p^2}\sqrt{\frac{m_i}{H_0}}\theta_i^2$$



Parameter Space I

Dark QCD Scale: $\Lambda_{\mathrm{dQCD}} \sim F_\pi \gtrsim 10^{11}\mathrm{GeV}$

Dark Quark Mass:

$$m_q \sim m_\pi / F_\pi \lesssim 10^{-20}\mathrm{eV}$$

Scenarios:

- π-axion masses set by m_I , m_{II} , m_{III} , εF_π
- Degenerate quark masses $\Rightarrow$ 3 π-axion masses:

$$\sqrt{2m_qF_\pi}\ , \sqrt{3m_qF_\pi}\ , \sqrt{6m_qF_\pi}$$

Dark Photon Mass:

$$m_{\gamma'} \ll F_\pi \Rightarrow m_\pm \text{ superheavy}$$

Vs

$$m_{\gamma'} \gg F_\pi \Rightarrow m_\pm \propto \varepsilon F_\pi$$

Note neutral π-axion is stable even when dark photon is massless and "millicharge" is 1!

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Parameter Space II: Millicharge

$\varepsilon \ll 10^{-20}$	$\varepsilon F_\pi \sim \mathrm{eV}$	$\varepsilon \gg 10^{-20}$ (including $\mathcal{O}(1)$)
charged pions ultralight	charged pions in eV-TeV range	charged pions superheavy
π-axions extremely weakly coupled to SM	Potentially interesting size of coupling	Coupling relevant to axion-detection experiments
Constraints on millicharged particles trivially satisfied	Charged pions constrained by variety of probes (e.g. stellar cooling)	Charged pions too heavy too subdominant to be constrained by their millicharge

Note neutral π-axion is stable even when dark photon is massless and "millicharge" is 1!

Fuzzy π-axions

Maleknejad, EM '22

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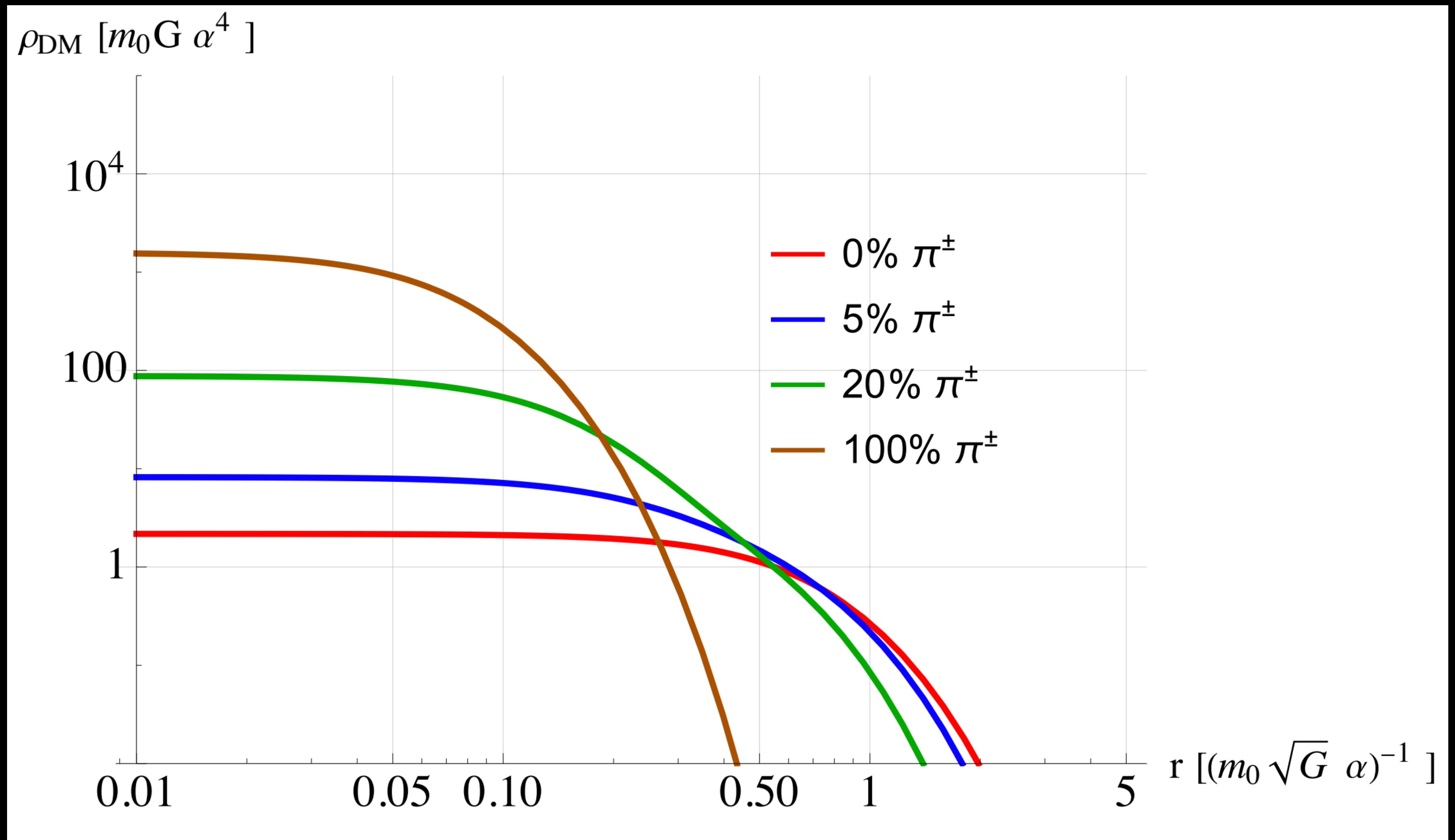
Fuzzy-ULP DM Halos & Boson Stars

$(N_f = 2)$

$$\nabla^2 \psi_0 = (V - E)\psi_0$$
$$\nabla^2 \psi_1 = (V - E)\psi_1$$
$$\nabla^2 \psi_2 = (V - E)\psi_2$$

$$\pi^{\pm} = \pi^1 \pm i\pi^2$$

$$\nabla^2 V = 4\pi G m_0 |\psi_0|^2 + 4\pi G m_{\pm}(|\psi_1|^2 + |\psi_2|^2)$$



Diversity of DM Halo Profiles

The WIMPZilla Connection: Dark Baryons

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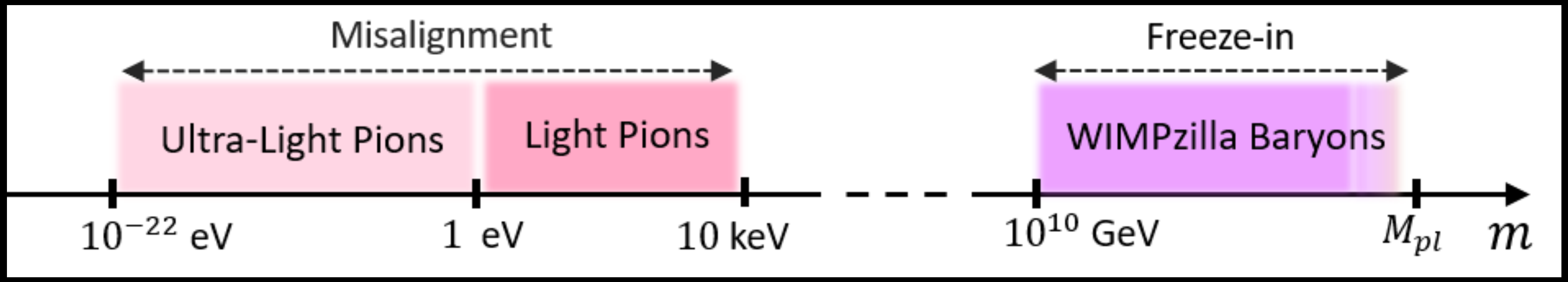
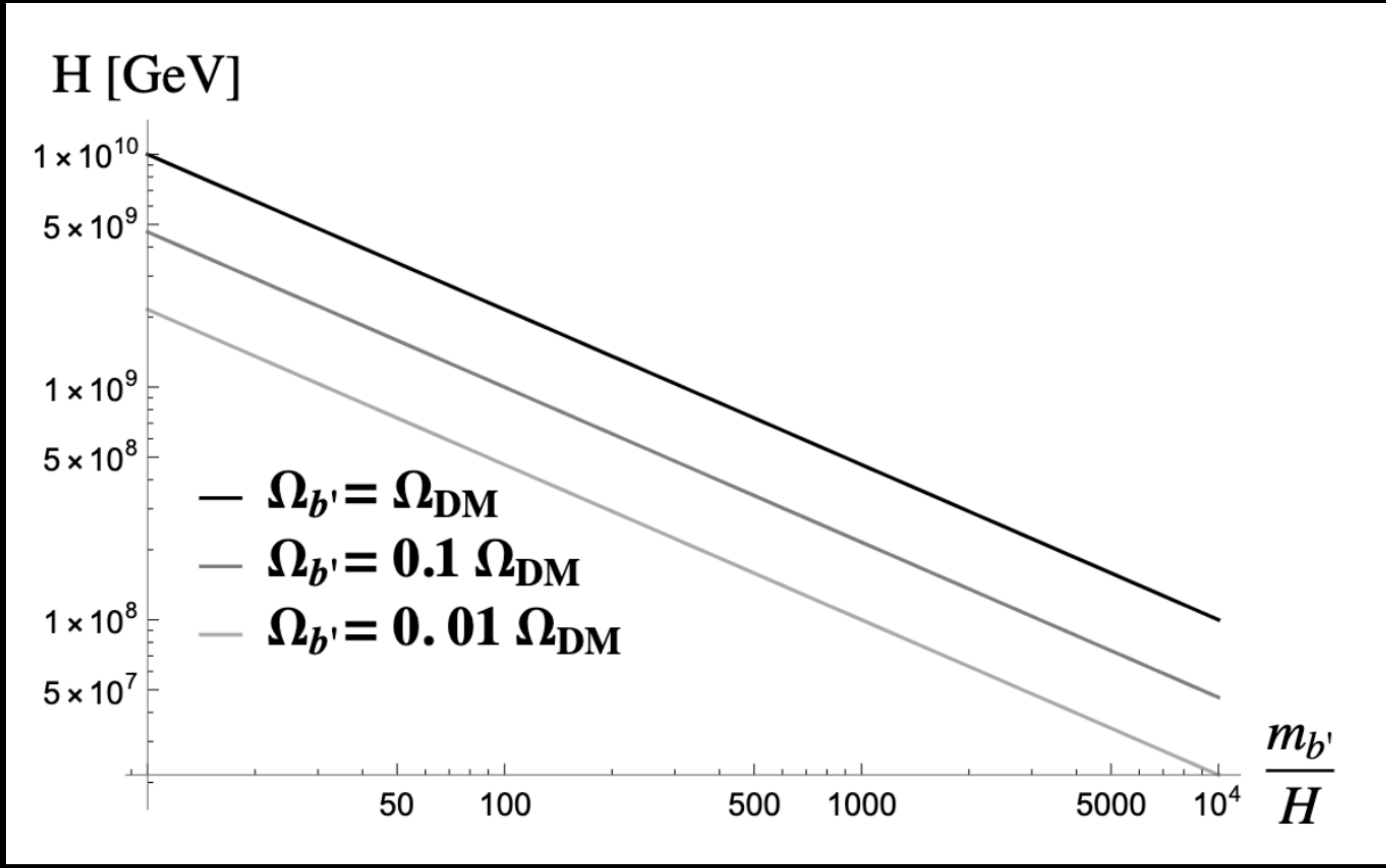
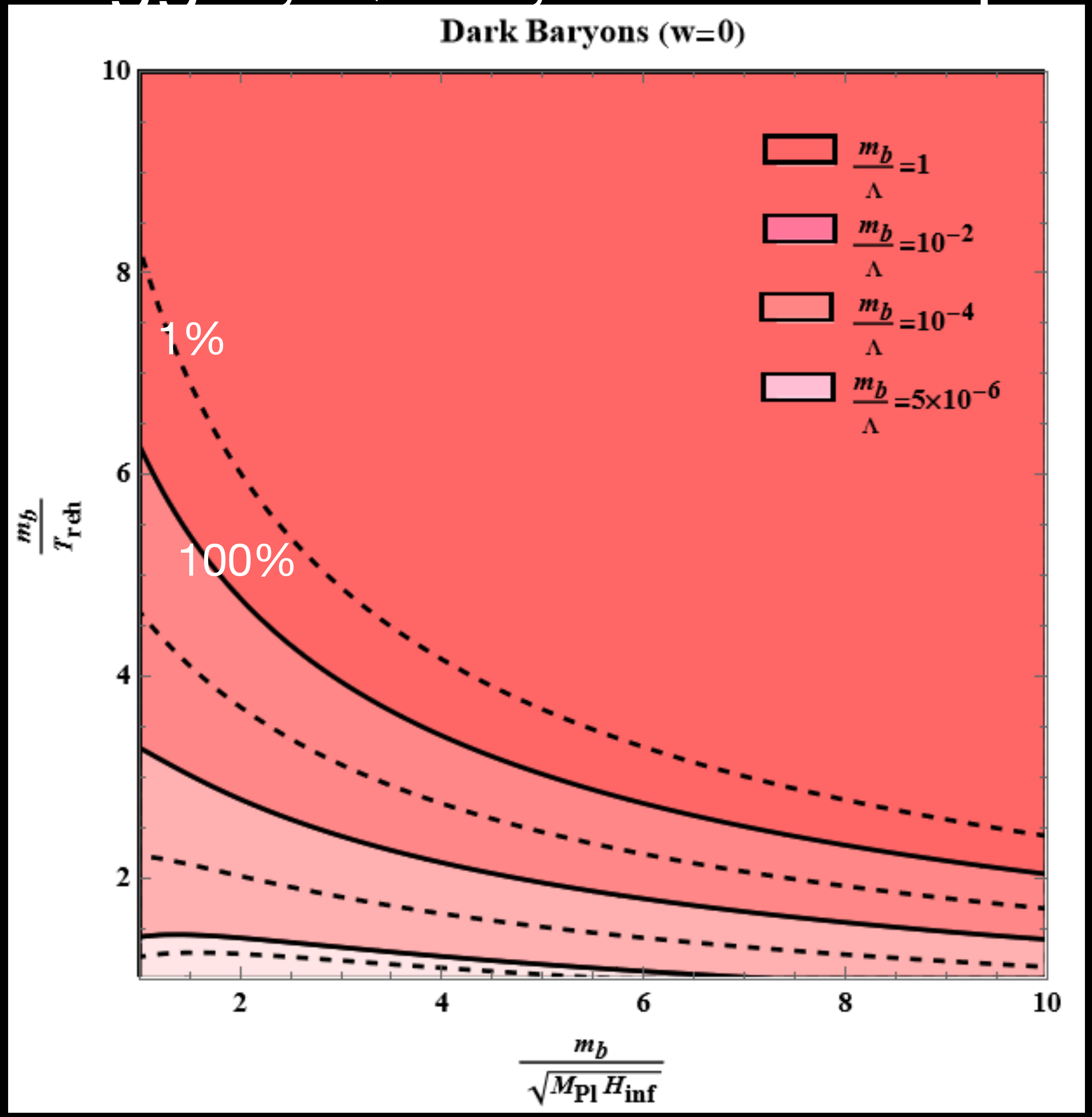
Maleknejad, EM '22



Gravitational Production from Inflation:



Freeze-In Production: Higgs-, QED-,or inflaton- portal



$\Lambda \equiv \Lambda_H / y\ ,\ \Lambda_\phi / \lambda\ ,\ m_{b'}/\epsilon$

Experimental Arenas

Parity-odd portal: $\mathscr{L} \sim g_{\pi\gamma\gamma}\pi F\tilde{F}$

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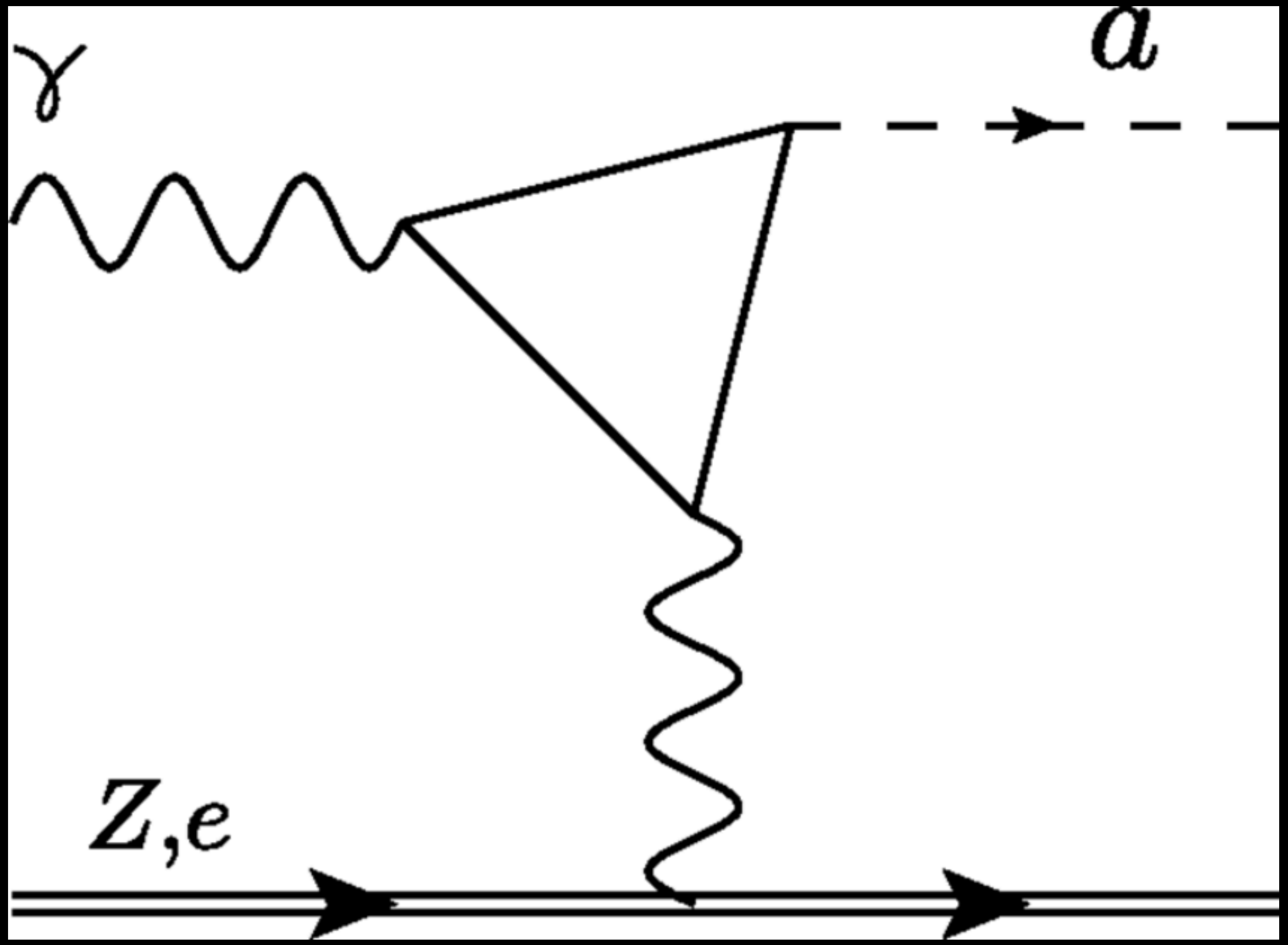
Recent review:
Adams et al Axion DM Snowmass

Experiments such as ADMX

- Axion-photon couplings in strong B-field background



Neutral pseudo-scalar pions have coupling:

$$g_{\pi\gamma\gamma} \sim c\frac{\alpha_e \varepsilon^2}{F_\pi}$$

Five neutral π-axions

$\Rightarrow$ Multiple distinct resonances

But $\varepsilon-$suppressed
relative to conventional axion

Note: $\tau_{\pi^0} \sim H_0^{-1}\left(\frac{F_\pi}{\text{TeV}}\right)^2\left(\frac{0.3\text{eV}}{m_{\pi^0}}\right)^3\frac{1}{\varepsilon^4}$ $\Rightarrow$ **Can have $\varepsilon = \mathcal{O}(1)$!**

$m_\pm \sim \varepsilon F_\pi$

Parity-even portal

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Experiments such as Atomic Clocks **Arvanitaki, Huang, Tilburg '15**

$$\mathscr{L} = \lambda \frac{\varepsilon^2}{M^2} |\pi_i|^2 F_{\mu\nu} F^{\mu\nu} + h.c.$$

$$\pi \sim \pi_0 \sin(mt + \delta) \qquad \Rightarrow \alpha_e(t) = \alpha_e \left(1 + \frac{2\lambda e^2}{\Lambda^2} \varepsilon^2 \sum_i |\pi_{i,0}|^2 \sin^2(m_i t + \delta_i) \right)$$

- Multiple (light) fields ⇒ multiple incoherent contributions
- Benchmark needed for detection:

$$\frac{\rho^i_{\rm DM} \varepsilon^2}{M^2 m^2_{\pi_i}} \gtrsim 10^{-15}$$

Example: Fuzzy π-axion, and $M = M_W = gv$,
Need tiny gauge coupling: $g < 10^{-8} \varepsilon$

π-axion Star Instability Via Parametric Resonance

Amin, Mou '20
Amin, Mou, Saffin 21
Du et al. '23 ("Axion Star Explosions")
Chung-Jukko et al. '23

$$A''_\pm + \left(k^2 + B_\pm(t)k + C(t)\right) A_\pm = 0$$

$[\varphi \equiv mt + \delta]$

$$B_\pm(t) = \frac{\lambda_2}{\Lambda_2^2}\varepsilon^2 \sum_{i,j}^{9} \pi^c_{i,0}\pi^c_{j,0}(2\cos(\theta_i - \theta_j))\Big[m_i \cos\varphi_i(t)\sin\varphi_j(t) + m_j \sin\varphi_i(t)\cos\varphi_j(t)\Big]$$
$$+\frac{\lambda_4}{\Lambda_4^2}\varepsilon^2\Big\{\sum_{i,j}^{6} \pi^c_{i,0}\pi^c_{j,0}(2\cos(\theta_i - \theta_j)) + \sum_{i,j}^{5} \pi^r_{i,0}\pi^r_{j,0}\Big\}\Big[m_i \cos\varphi_i(t)\sin\varphi_j(t) + m_j \sin\varphi_i(t)\cos\varphi_j(t)\Big]$$
$$\pm\frac{\lambda_3}{F_\pi}\varepsilon^2 \sum_{i}^{5} \pi^r_{i,0} m_i \cos\varphi_i(t),$$

$$C(t) = \lambda_1 \varepsilon^2 e^2 \sum_{i,j}^{9} \pi^c_{i,0}\pi^c_{j,0}\cos(\theta_i - \theta_j)\sin\varphi_i(t)\sin\varphi_j(t)$$

Simple charged-pion coupling, $|\pi^\pm|^2 A_\mu A^\mu$
can dramatically enhance parameter resonance

Jaeckel, Schenk '21

Summary

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π-Axion	Axion
confining gauge theory, Chiral symmetry breaking	complex scalar, spontaneously broken global U(1) symmetry
Many pions, mass splitting due to charges	1 axion per complex scalar
WIMPZilla: dark baryons	WIMPZilla: radial field
Real and complex neutral, and charged	Real neutral
Other degrees of freedom: dark Electroweak , η', glueballs . . .	Other degrees of freedom: Model dependent
Interactions: Parity-odd and parity-even	Parity-odd couplings

$(\mathrm{e.g.}\, |\pi^{\pm}|^2 A_\mu A^\mu)$

QCD Axiverse String Axiverse

QCD Axiverse	String Axiverse
SM physics: pions	BSM Physics: Euclidean D-branes (instantons) and gaugino condensation on D7 branes
1 non-pert effect (confinement)	1 distinct non-pert effect per axion
$N_f^2 - 1$ π-axions	• 1 to 10 to 100's of axions — but surprisingly difficult to engineer!
Natural expectation is tightly packed discrete spectrum of masses	Natural expectation is log distribution of masses

$\pi-$axions in String Theory

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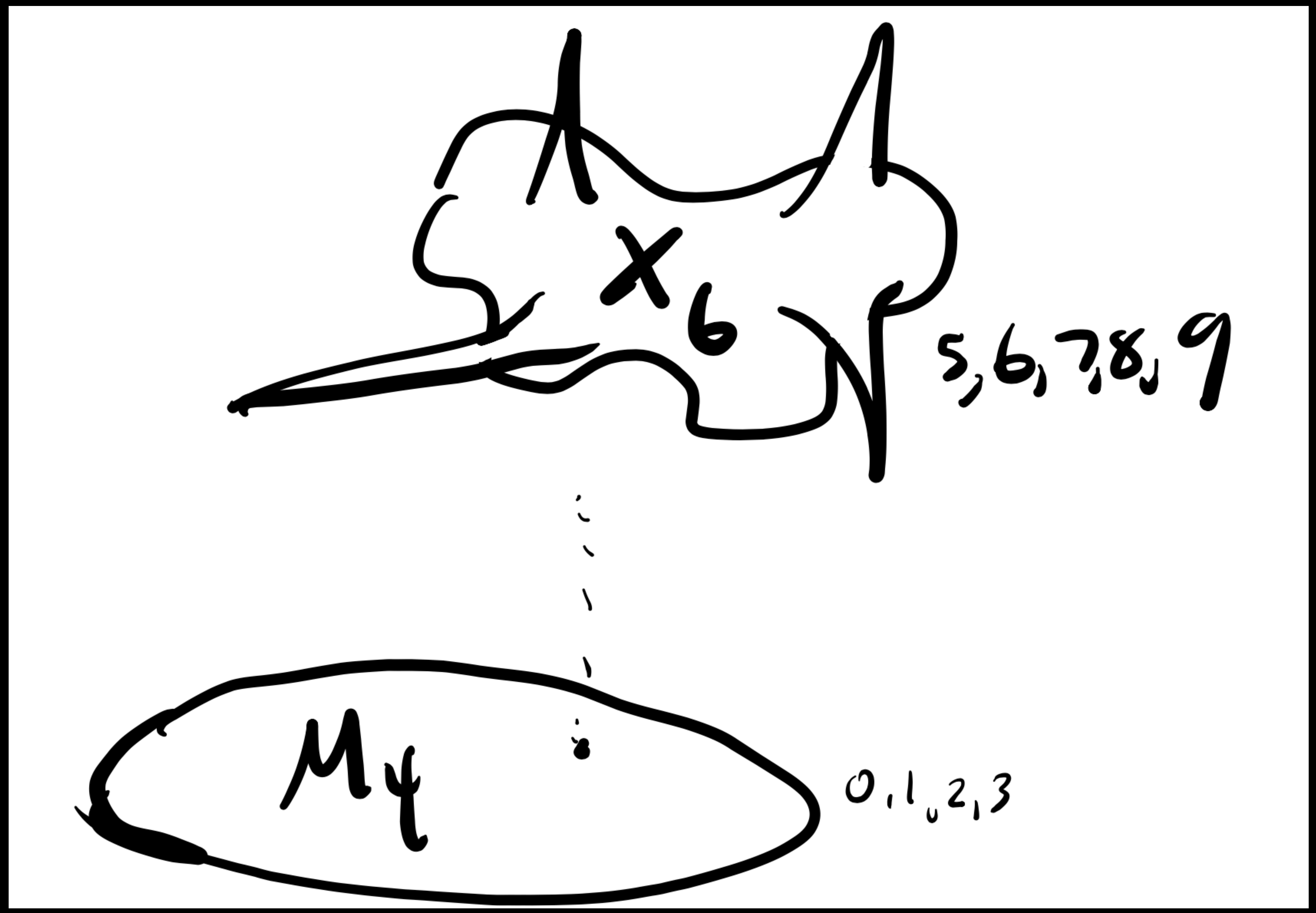

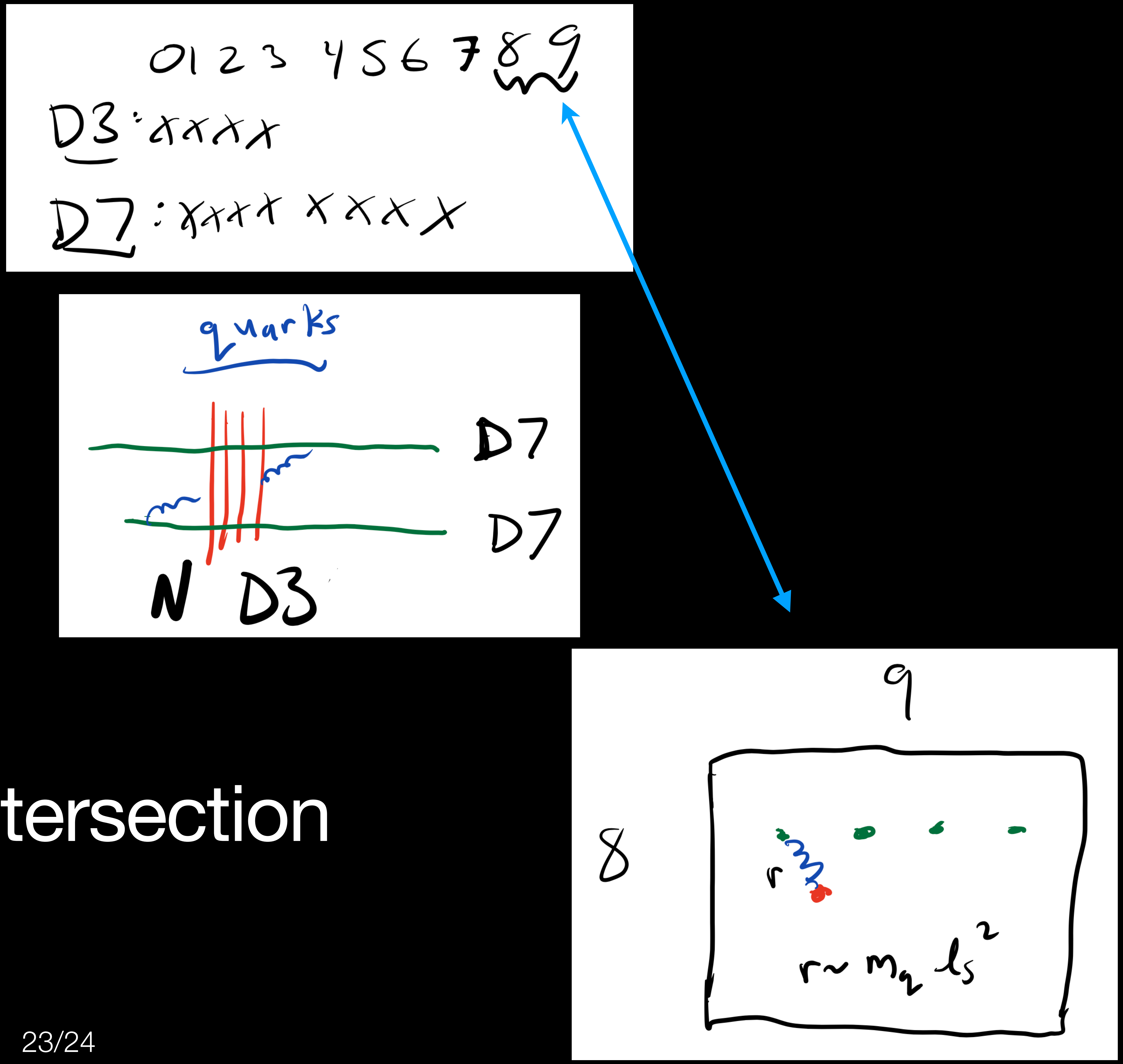

Light $\pi-$axions $\Leftrightarrow$ near-intersection

Take-Home Messages

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- SM Physics can provide an ‘axiverse’: the π-axiverse of a dark SM
  - Dark SM gets you the millicharges, flavor violation, etc.
- DM candidate: π-axion DM
  - DM can be mixture of real scalar, neutral complex scalars, and millicharged complex scalars
  - Natural theory expectation is tightly packed discretum of masses
- Detection: mixture of parity-odd and parity-even signals

Lots to do!

1. Constraints Plot! Statistical distribution of predictions
2. Millicharge signatures
3. Imprint on CMB and LSS
4. Uncovering the iceberg (dark baryon production)
5. Dark Energy , Early Dark Energy

Thanks!

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Sec 1: Introduction (5 slides)

- DM
- Axion: Strong CP problem
- Axion DM
  - Later Axion —> ULDM
    - Axion of 1979 was tip of an iceberg
- Didn’t work out: QCD Axion probably not DM
- String Axiverse: huge range of masses possible, huge number of species
    - Motivates many papers!

Stephon:

- things we know that work (SM physics)
- Weinberg said pion must PNGB on very general grounds
- Modularity:use SM physics tackle DM

Sec 2: The pi-axion and pi-axiverse (5 slides)

- SM Pions as PNGB’s —> Weinberg & Nambu
- Dark SM
- Spectrum of masses
- Interactions

Stephon: footnote cite Composite Axion paper

Sec 3: pi-axion DM (5 slides)

- Stability, relic density
- Parameter space
- Pi-axion-electrodynamics
- Pi-axion stars

Stephon side-note: possibility to solve strong CP problem in SU(3)? imagine we had a dark sector with 1 extra quark that is identically massless and charged under SU(3) . The massless quark lets you rotate away the theta angle

Sec 4: Detection (5 slides)

- Re-summarize interactions
- Direct Detection: parity odd
- Direct Detection: parity even
- Parametric Resonance & pi-axion stars

Sec 5: Discussion (3 slides)

- Summary
- Pi-axions in string theory
- Closing thoughts: axions are tip of iceberg; string theory not needed to motivate large number of ALPs
- Future work & Open Questions

Photon Portal to the SM

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SM couplings

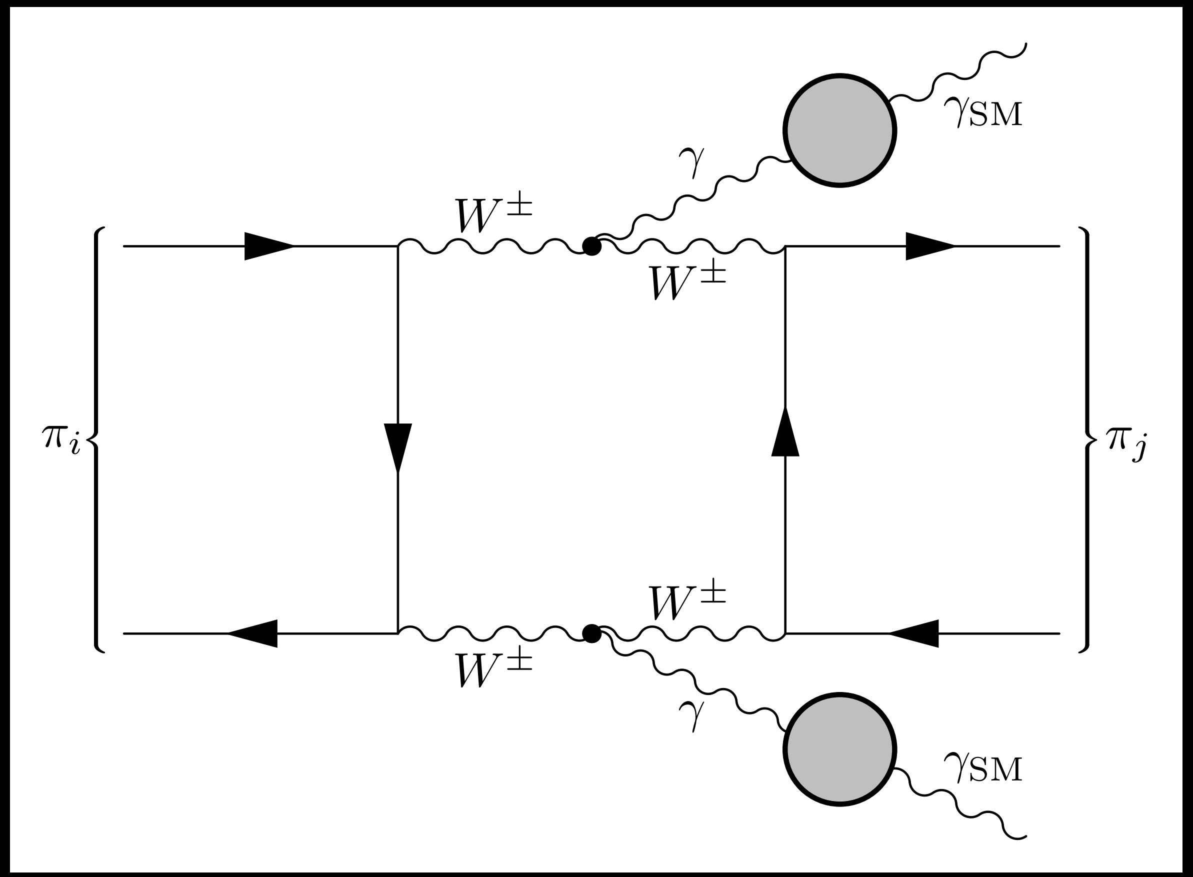
$$\mathcal{L}^{(1)} = \frac{\lambda_1}{2F_\pi}\epsilon^2\left(\pi^0\right)F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathcal{L}^{(2)} = \frac{\lambda_2}{2}\epsilon^2\left(\pi^+\pi^-\right)A_\mu A^\mu$$

Pion mixing

$$\mathcal{L}^{(3)} = \frac{\lambda_3}{2\Lambda_3^2}\epsilon^2\left(\pi^+\pi^-\right)F_{\mu\nu}F^{\mu\nu}$$

$$\mathcal{L}^{(4)} = \frac{\lambda_4}{2\Lambda_4^2}\epsilon^2\left(\pi_i\pi_j\right)F_{\mu\nu}F^{\mu\nu}$$



Rates:

$$\Gamma_{(1)} = \varepsilon^4\frac{\lambda_1^2\alpha_e^2}{64\pi^3}\frac{m_i^3}{F_\pi^2}.$$

$$\Gamma_{(2)} = \frac{\lambda_2^2\varepsilon^4}{16\pi^3}\frac{(m_i-m_j)(m_i^2+m_j^2)}{m_i^2}$$

$$\Gamma_{(3)} = \frac{\lambda_3^2\varepsilon^4}{\Lambda_3^4}\frac{1}{192(2\pi)^3}\frac{(m_i-m_j)(m_i^2+m_j^2)^3}{m_i^2}$$

$$\Gamma_{(4)} = \frac{\lambda_4^2\varepsilon^4}{\Lambda_4^4}\frac{1}{192(2\pi)^3}\frac{(m_i-m_j)(m_i^2+m_j^2)^3}{m_i^2}$$

Lifetime

$$\tau_{\pi^0} \sim H_0^{-1}\left(\frac{F_\pi}{\rm TeV}\right)^2\left(\frac{0.3{\rm eV}}{m_{\pi^0}}\right)^3\frac{1}{\varepsilon^4}$$

Pi-axion electrodynamics

(Nf=2 for simplicity)

$$\vec{\nabla} \cdot \vec{E} = \frac{g}{F_\pi} \vec{B} \cdot \vec{\nabla} \pi^0 - \epsilon^2 e^2 \pi^+ \pi^- V$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial E}{\partial t} = \frac{g}{F_\pi} \left(\vec{E} \times \vec{\nabla} \pi^0 - \vec{B} \frac{\partial \pi^0}{\partial t} \right) - \epsilon^2 e^2 \pi^+ \pi^- \vec{A}$$

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ULPs vs ALPs

Maleknejad, EM ’22

- UV completion is confining gauge theory
- N_f^2 pions, mass splitting due to charges
- WIMPZilla candidate: dark baryons
- Other *(unstable) degrees of freedom
- Can be charged

- UV completion is global U(1)
- 1 axion per U(1)
- WIMPZilla candidate: radial field; size modulus
- Neutral

Ultra-Light Pions: Composite ALPs from Confining Gauge Theory

<u>Deconfined phase</u>

Free quarks & gluons

Local SU(N)
+
Global Chiral Symmetry

$$SU(N_F) \times SU(N_f) \times U(1)_V \times U(1)_A$$

<u>Confined Phase</u>

Mesons, baryons

Local SU(N)
+
Chiral symmetry breaking

$$SU(N_F) \times SU(N_f) \rightarrow SU(N_f)$$

Pions!

ULPs and WIMPZillas

With Azadeh Maleknejad

Ultra-Light Pions **Superheavy Baryons**

Pions are a lot like axions:

Simplest case:

$$\Sigma_{ij} = \frac{F_\pi + \sigma(x)}{\sqrt{2}} \exp\left(\frac{2i\pi^a(x)\tau_a}{F_\pi}\right),$$

$$V(\pi) = \mathrm{Tr}[\Sigma^\dagger \boldsymbol{m}_\chi + \boldsymbol{m}_\chi^\dagger \Sigma] \rightarrow m_\pi^2 f_\pi^2 \cos\left(\frac{\pi}{f_\pi}\right)$$

$$m_{\pi^0} \sim \sqrt{\Lambda m_q}$$

$$F_\pi \sim \Lambda$$

ALP-like cosmological evolution: $m_{\pi_0} < \mathrm{eV}\ ,\ F_\pi \gtrsim 10^{10}\mathrm{GeV}$

$$\Rightarrow m_q < 10^{-19}\mathrm{eV}\ ,\ \Lambda \gtrsim 10^{10}\mathrm{GeV}$$

What comes along for the ride: **The rich structure of confining gauge theory!**

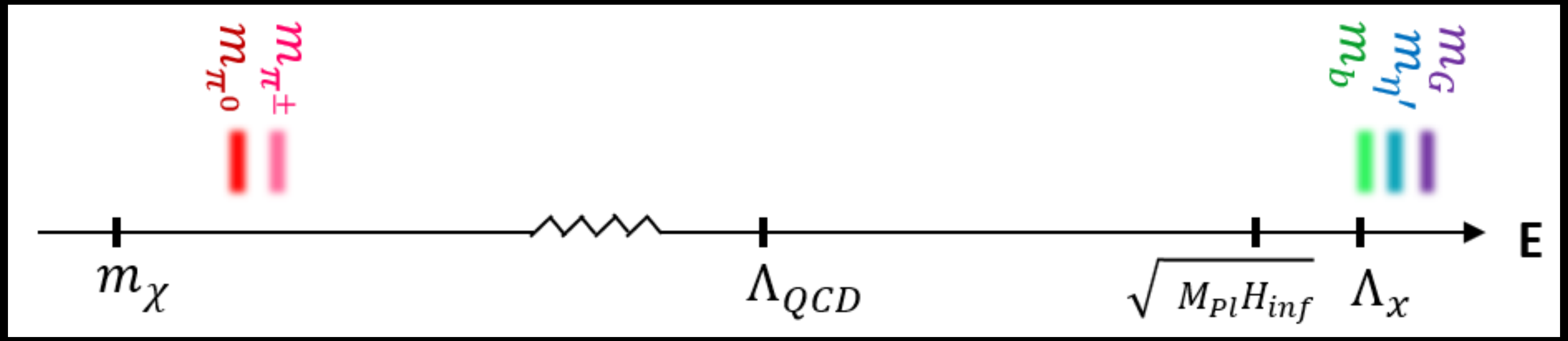
ULPs and WIMPZillas

Ultra-Light Pions Superheavy Baryons

With Azadeh Maleknejad

Spectrum:

Pions [stable]: neutral and charged Baryons [stable], eta', glueballs, ….

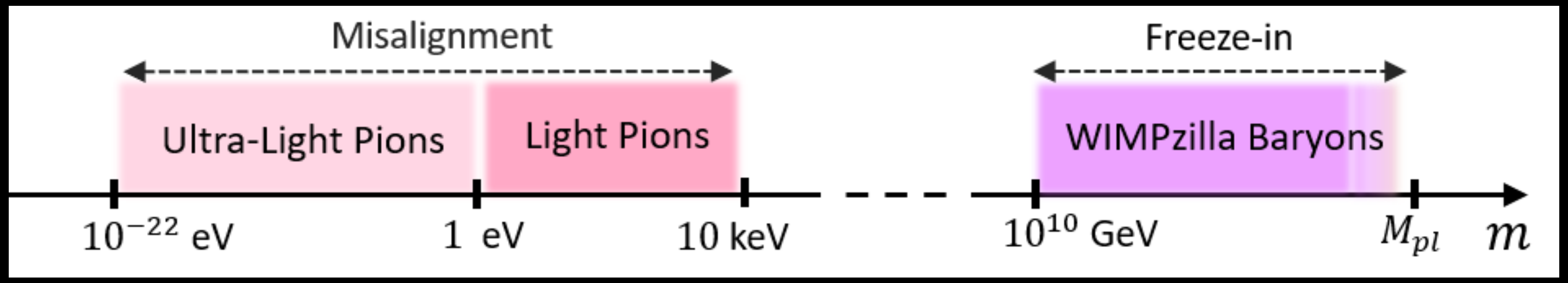


$$m_{\pi^\pm}^2 \simeq m_{\pi^0}^2 + F_\pi^2(\varepsilon_u - \varepsilon_d)^2$$

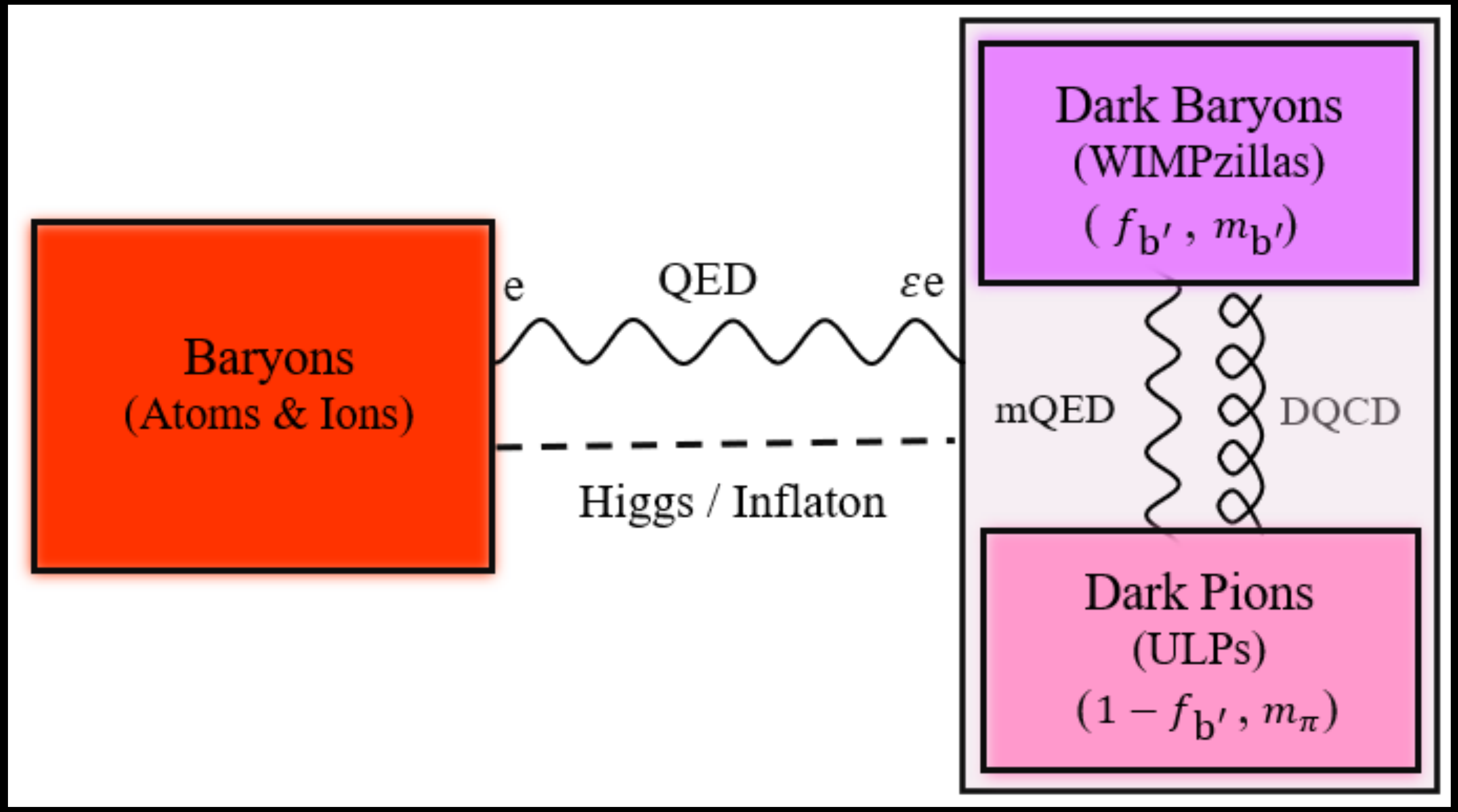
Milli-electric charge

$$m_{b'} \sim \Lambda$$

Production:



Portals to the Standard Model



DM is an admixture of superheavy and ultralight

Dark Baryon Production

Maleknejad, EM '22

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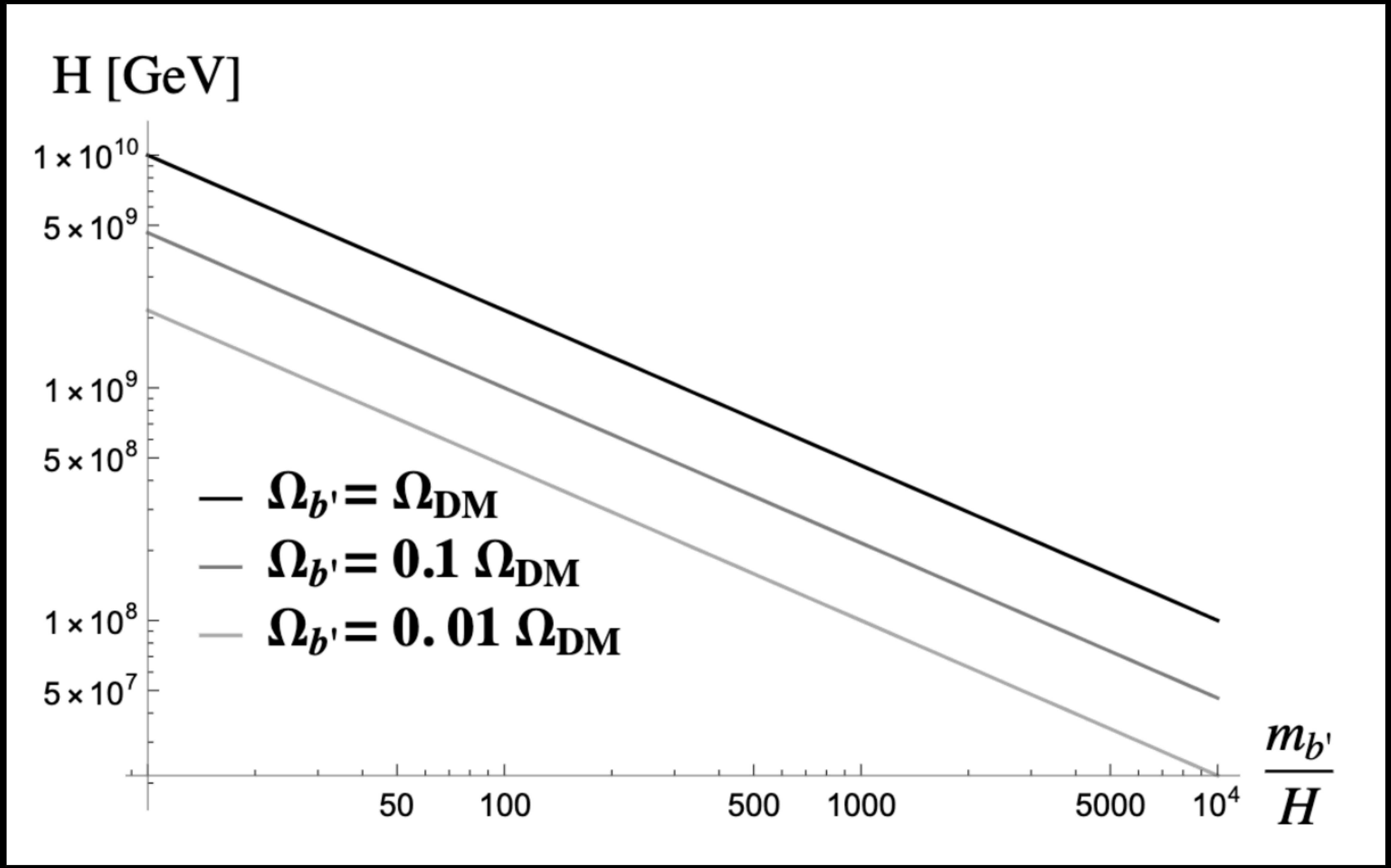
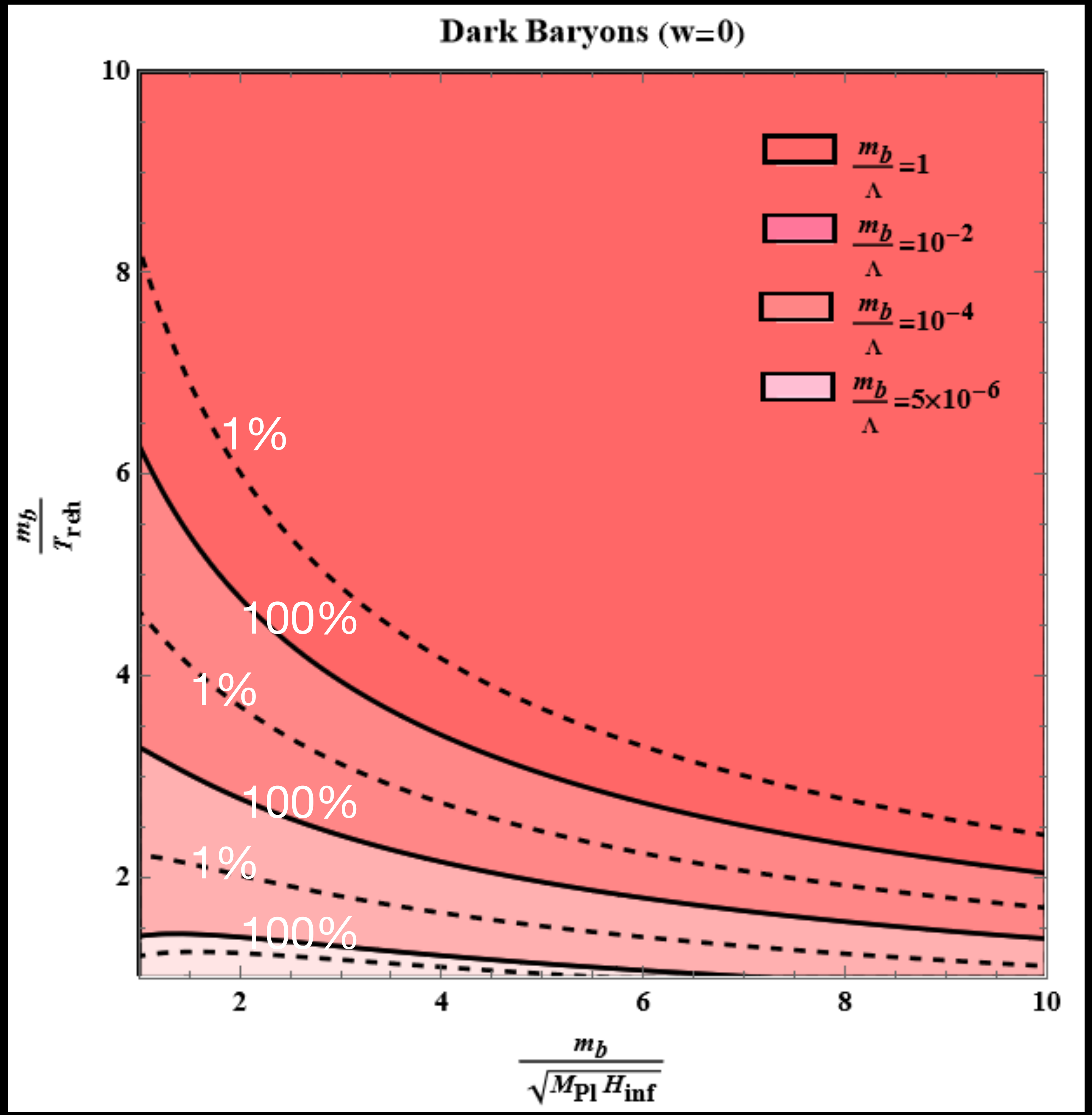
Gravitational Production from Inflation:



Freeze-In Production:
Higgs-, QED-,or inflaton- portal

$\Lambda \equiv \Lambda_H / y \ , \ \Lambda_\phi / \lambda \ , \ m_{b'}/\epsilon$



Fuzzy pi-axion

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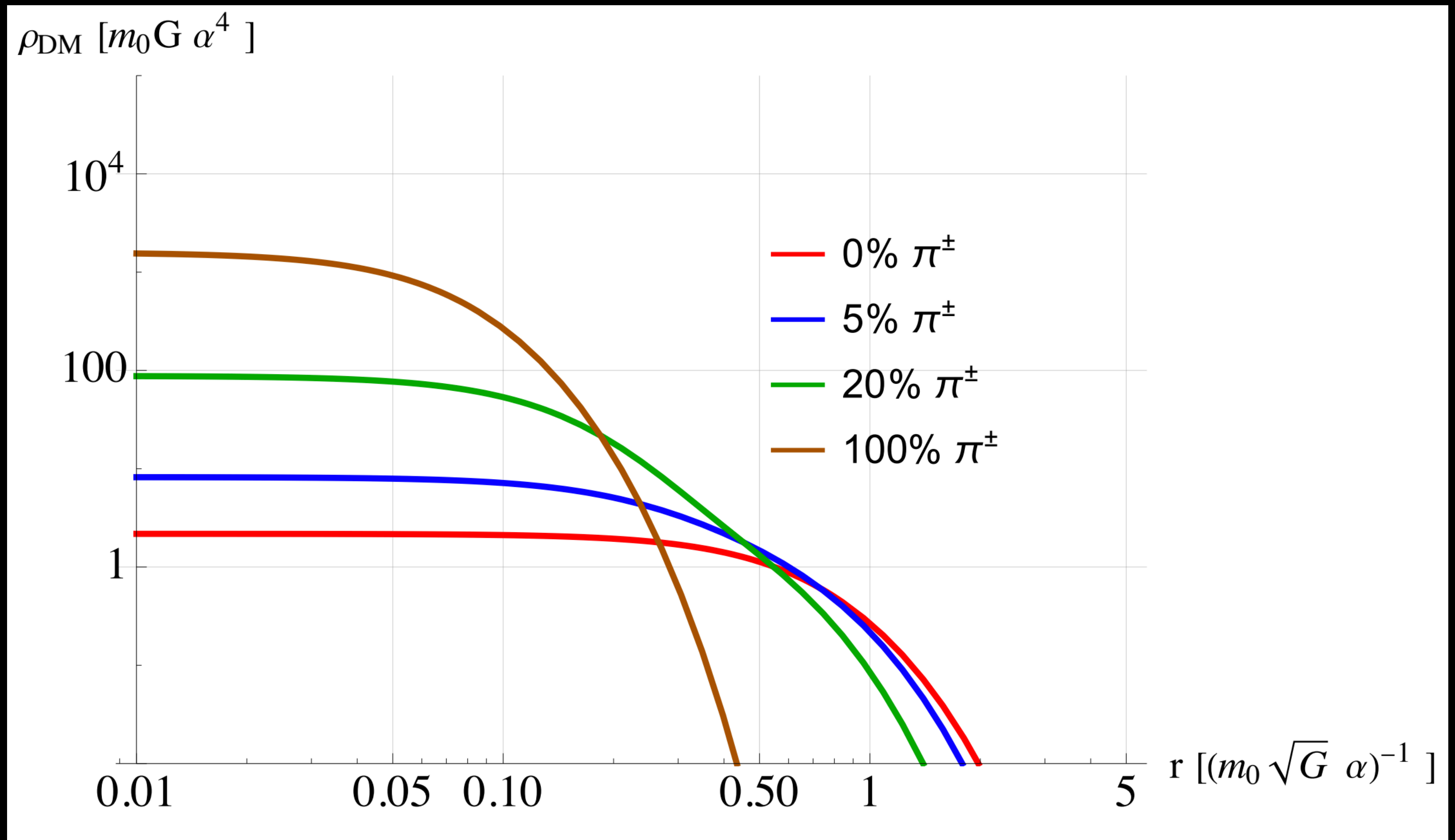
Fuzzy-ULP DM Halos & Boson Stars

$$\nabla^2\psi_0 = (V - E)\psi_0$$
$$\nabla^2\psi_1 = (V - E)\psi_1$$
$$\nabla^2\psi_2 = (V - E)\psi_2$$

$$\pi^{\pm} = \pi^1 \pm i\pi^2$$

$$\nabla^2 V = 4\pi G m_0 |\psi_0|^2 + 4\pi G m_{\pm}(|\psi_1|^2 + |\psi_2|^2)$$



Diversity of DM Halos

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ULP-WIMPZilla Particle Physics

Maleknejad, EM ’22

For “axion” experiments: ULP Electrodynamics

$$\vec{\nabla} \cdot \vec{E} = \frac{g}{F_\pi} \vec{B} \cdot \vec{\nabla}\pi^0 - \epsilon^2 e^2 \pi^+ \pi^- V$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial E}{\partial t} = \frac{g}{F_\pi} \left(\vec{E} \times \vec{\nabla}\pi^0 - \vec{B}\frac{\partial \pi^0}{\partial t} \right) - \epsilon^2 e^2 \pi^+ \pi^- \vec{A}$$

WIMPzilla signatures:

Snowmass2021 Cosmic Frontier White Paper: Ultraheavy particle dark matter

Direct detection; High energy cosmic rays; high energy neutrinos

ULPs vs ALPs

Maleknejad, EM '22

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ULPs in String Theory

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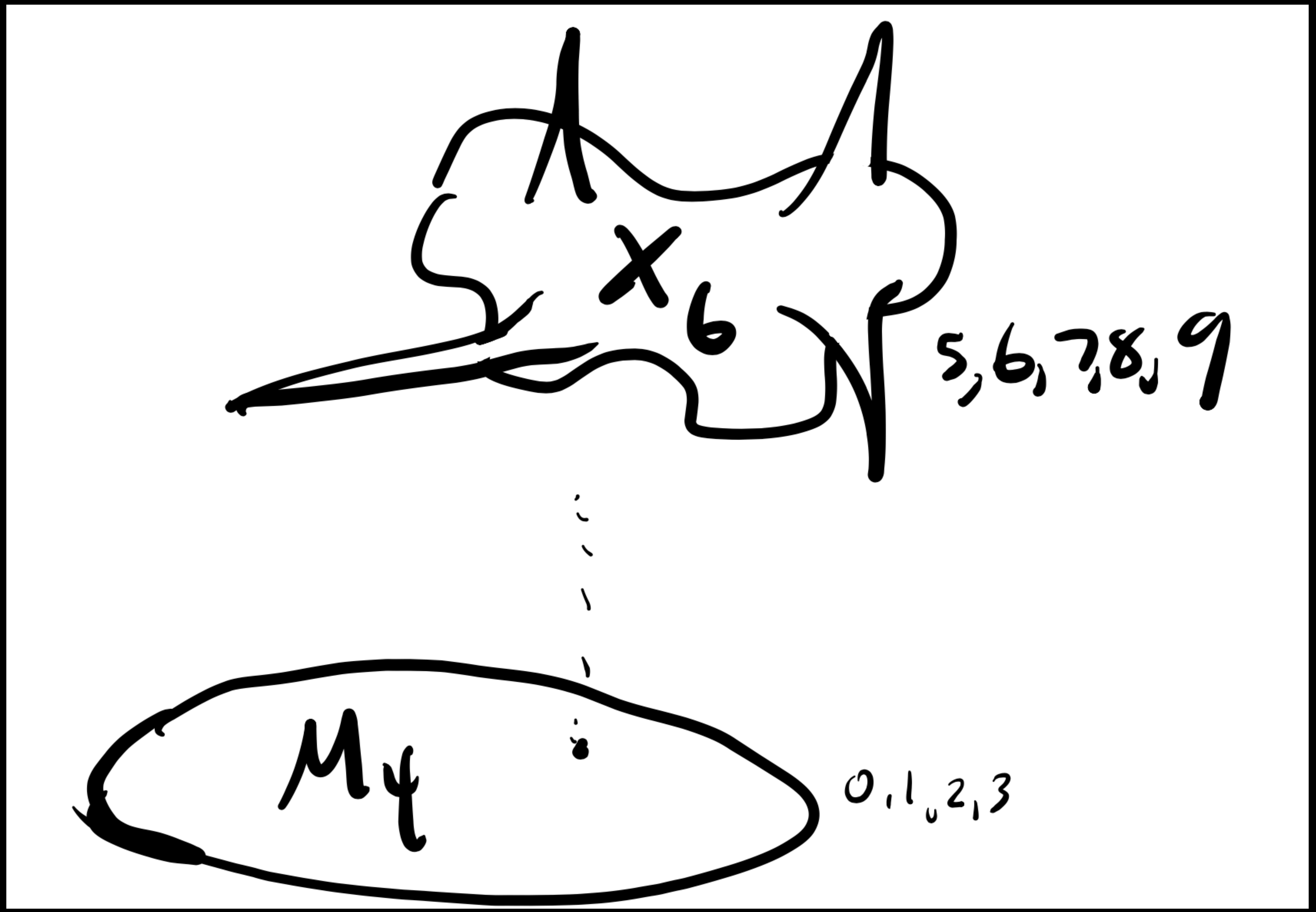

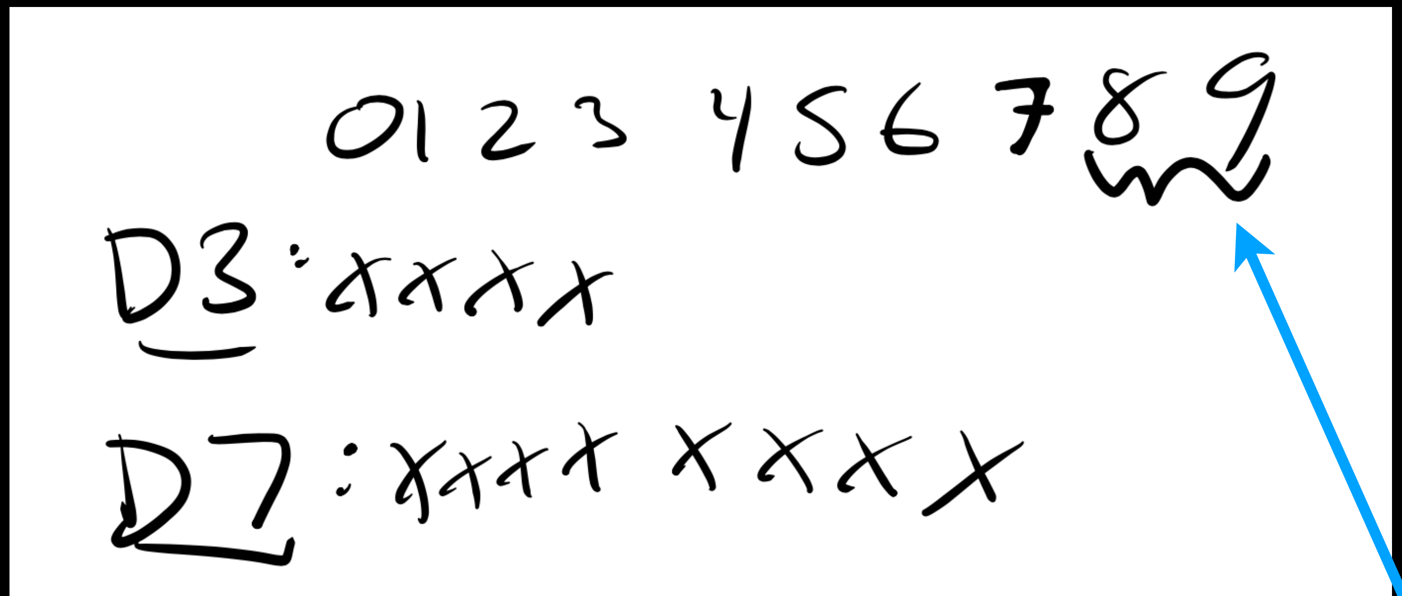

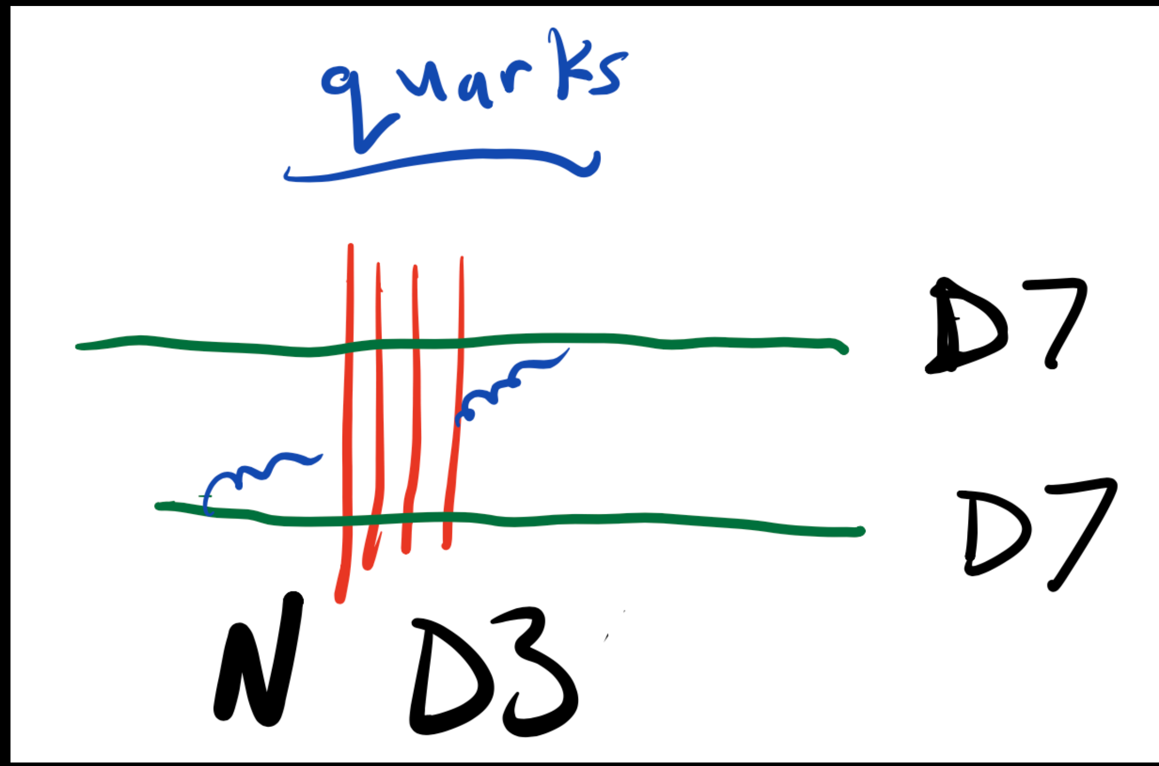

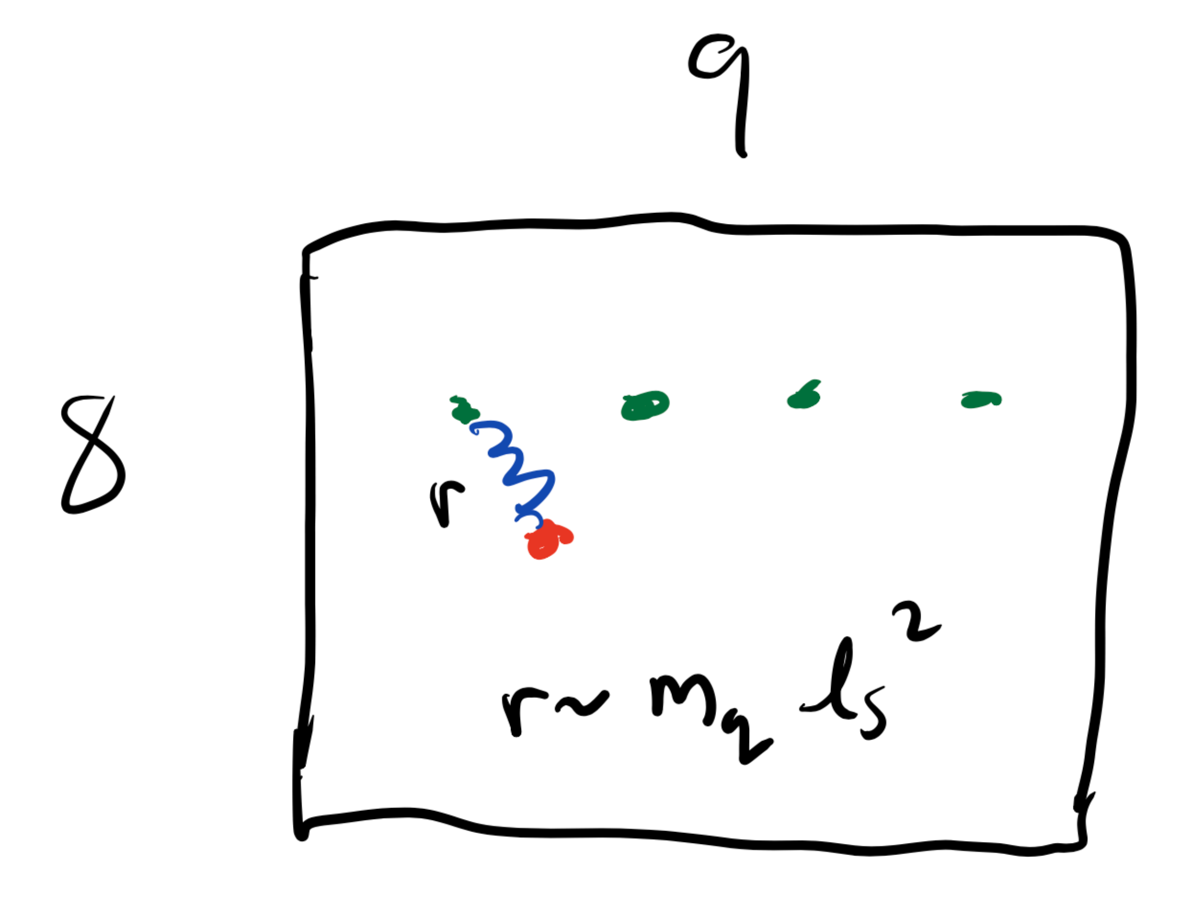

ULPs = near-intersection

Astro probes of Cosmo CMT:

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1. Astrometry & DM substructure: Tracking the motions of stars in our own Milky Way. Fuzzy Dark Disk Universe. [EM, Bramburger, Alexander, 1901.03694]

2. Strong Gravitational Lensing by distant galaxies and galaxy clusters. Vortices! [Toomey, EM+ arXiv:1909.07346]

3. The Cosmic Web: Rotation of the largest structures in our universe, from vortices! [Capanneli, EM, Ferreira, Alexander arXiv:2111.03061]

(Also new particle physics!)

1. Why are we here? Connections to matter-antimatter asymmetry
2. Interactions with neutrinos: oscillating neutrino masses
3. Interactions with standard model quarks

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Summary

There is lots of room at the bottom! Ultralight Dark Matter can have a rich stucture:

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ULP-WIMPZilla is a prototypical example

There is lots of room at the bottom! Ultralight Dark Matter can have a rich stucture:

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ULP-WIMPZilla is a prototypical example

Lots left to explore:

Low-Hanging Fruit:

- Diversity of DM halos
- Uncovering the icebergs: interplay of ultralight superheavy DM constraints

High-Hanging Fruit:

- numerical simulations of structure
- properties of vortices in different models

Crazy ideas:

— BKT transition in fuzzy dark disk?
— holographic description of condensate phases of dark QCD?

Thanks!

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Observables

Model-independent:

- Soliton core of DM halos, excitations described by Schrodinger equation
- Interference of condensate wave function
- vortices
  - from interference, angular momentum
  - spinning cosmic filaments, strong lensing

Model-Dependent:

- Size and profile of solitonic core
- Interactions with standard model
  - Electromagnetic signatures
- Other degrees of freedom from “UV” completion: e.g. dark baryons

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STUMPs vs. Ultra-Light Bosons

1. Different effective theory of interactions: e.g.,

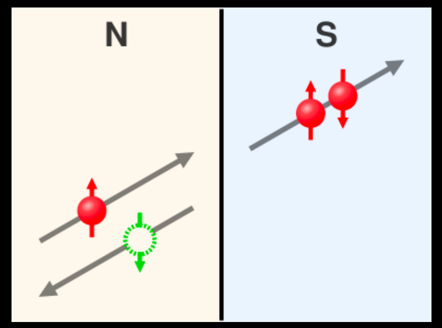
$$\mathcal{L} = \frac{g}{\Lambda_B^2}\bar{N}N\bar{f}f$$

→ Dark QCD signatures at colliders

2. Superconducting Halo Cores:

→ 2.1 superconducting vortices formed in mergers (and high energy cosmic rays?)

→ 2.2 Andreev Reflection [Andreev, 1964]



3. Signatures of dark pion emission?

$$\mathcal{L}_{NN\pi} \simeq \alpha \frac{\partial_\mu \pi}{f_\pi}\bar{N}\gamma^\mu\gamma^5 N$$

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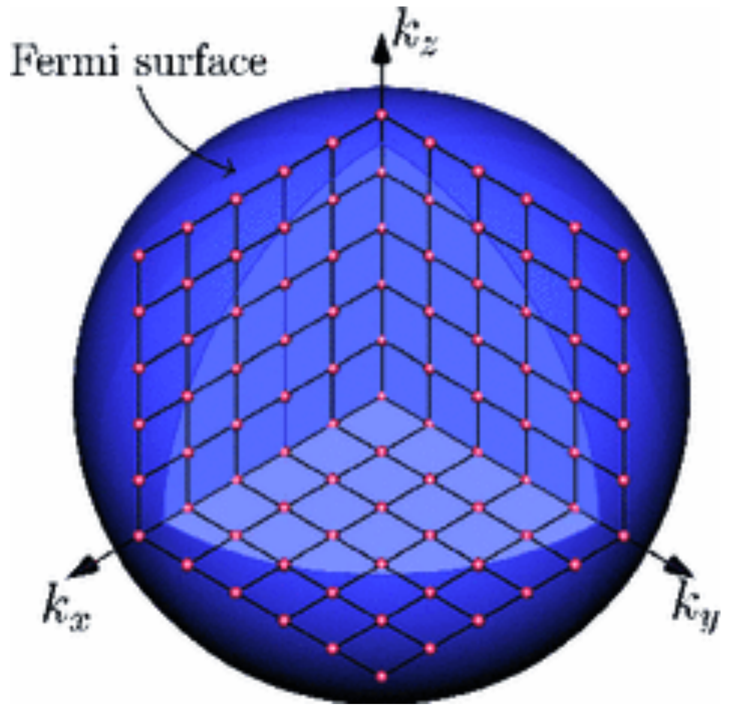
Ultra-light (sub-eV) Fermion DM? The Tremaine-Gunn Bound

[Boyarsky et al, 0808.3902]

v2: Pauli Exclusion Principle :



1. Fermions fill up a Fermi Sphere
2. Heavy object $\longleftrightarrow$ high momentum particles
3. Escape velocity $\longleftrightarrow$ mass bound: $m_{\rm DM} > 100\,{\rm eV}$

[Tremaine-Gunn, 1979]

v1: Liouville Theorem:

1. Early times = Fermi-Dirac distribution
2. Late time = Isothermal halo
3. No collisions or dissipation $\longrightarrow$ maximum of distribution conserved

$$\longrightarrow \quad m_{\rm DM} > 100\,{\rm eV}$$

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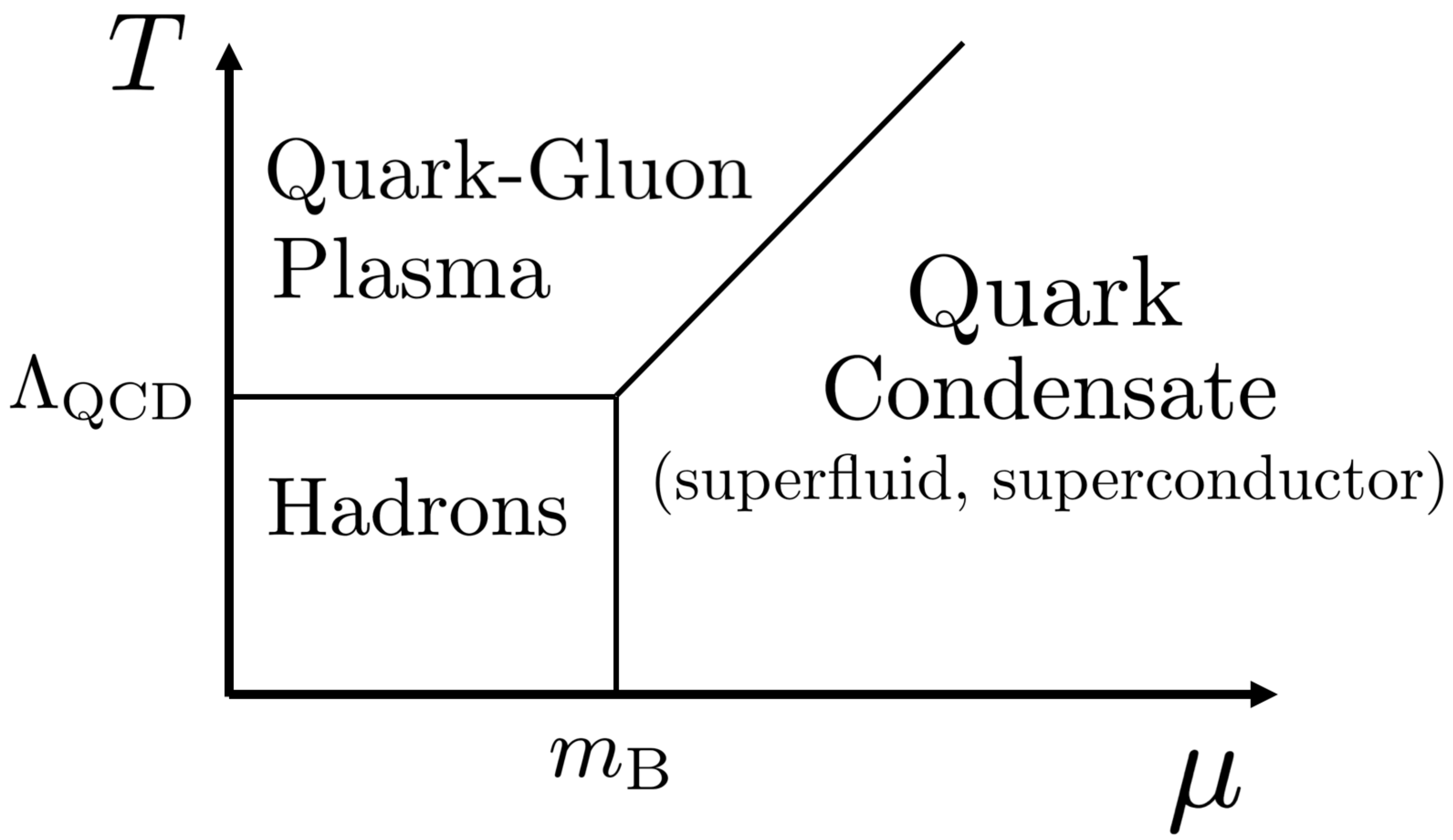
(Dark) QCD at High Density



Ultra-Light Dark QCD:

$m_B \lesssim 0.1\,\mathrm{eV}$

[Alford, Schmitt, K. Rajagopal, Schafer, Rev. Mod. Phys. 80 (2008).]

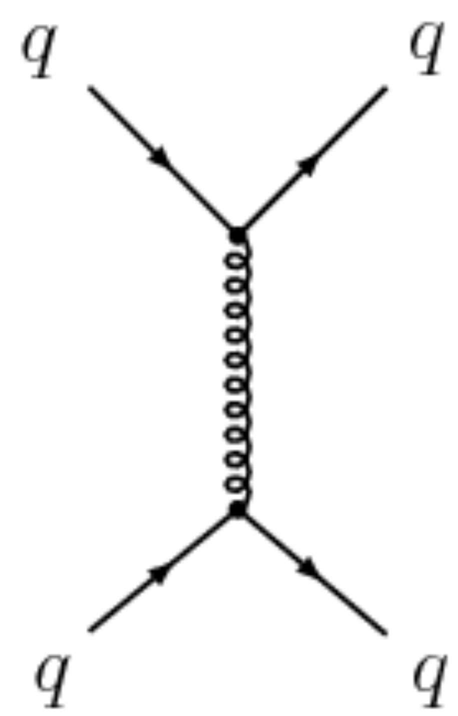
When $n^{1/3} > m_B \sim \Lambda_{\rm QCD}$:

$$\langle q\, q\rangle = \langle q^i_{\alpha a} q^j_{\beta c} \epsilon^{ac}\rangle = \Delta \epsilon^{ij}\epsilon_{\alpha\beta}$$

Breaks Color x Flavor ⟶ Color-Flavor

="Color Flavor Locking"

QCD-version of BCS: Color **Superconductor**



Attractive interaction: anti-symmetry is attractive

$$\mathcal{M}_{qq\to qq} \propto -\mathrm{Tr}\, T^a_{ij} T^a_{kl} = -\frac{1}{2}\left(\delta_{il}\delta_{jk} - \frac{1}{N_c}\delta_{ij}\delta_{kl}\right) \text{ can be } > 0$$

"Cooper Pairing": $$\Delta \simeq \frac{10^5 \mu}{g^5} e^{-\frac{3\pi^2}{\sqrt{2}g}}$$

[Dark QCD: EM, Spergel, Alexander arXiv:1801.07255]

TG vs BCS

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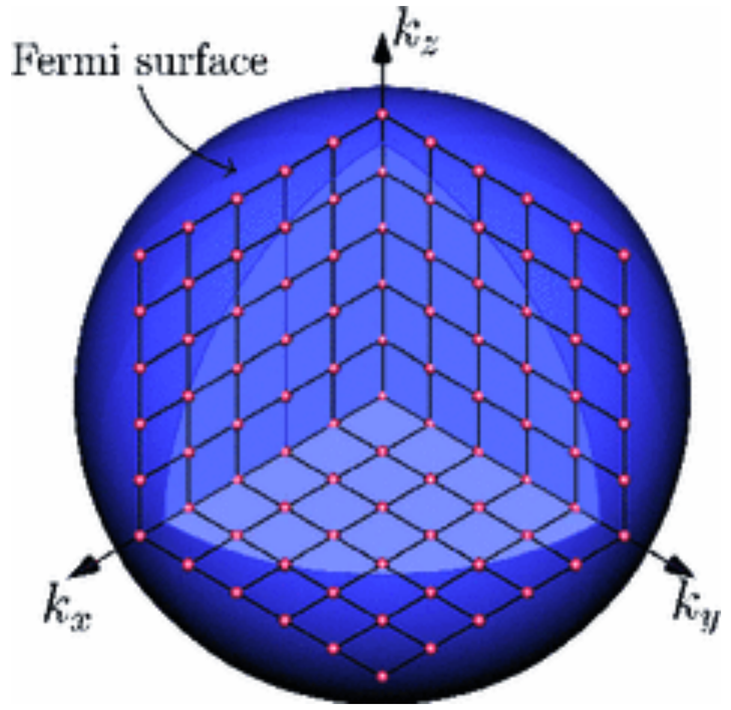
Pauli Exclusion Principle Bound?

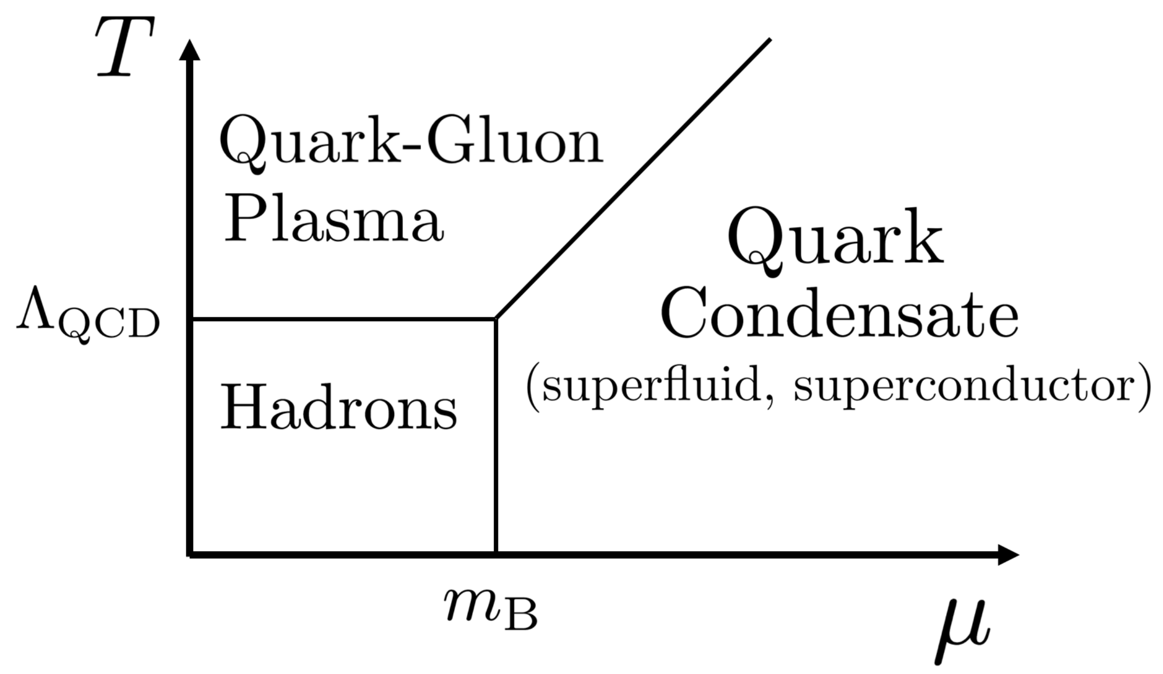
$$\langle \psi_{\vec{k}} \psi_{-\vec{k}} \rangle = \varphi$$

PEP obeyed, but no escape velocity bound.



Louisville Theorem?

Both collisions and dissipation!
Final configuration governed by hydrostatic equilibrium and an equation of state



$$\Omega = -a_4\mu^4 + a_2\mu^2 + B_{\rm eff}$$

[Alford et al. 0411016]

Ultra-light Dark QCD is a loophole to TG bound

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DM Core = STUMP "Neutron Star"

TOV equations:

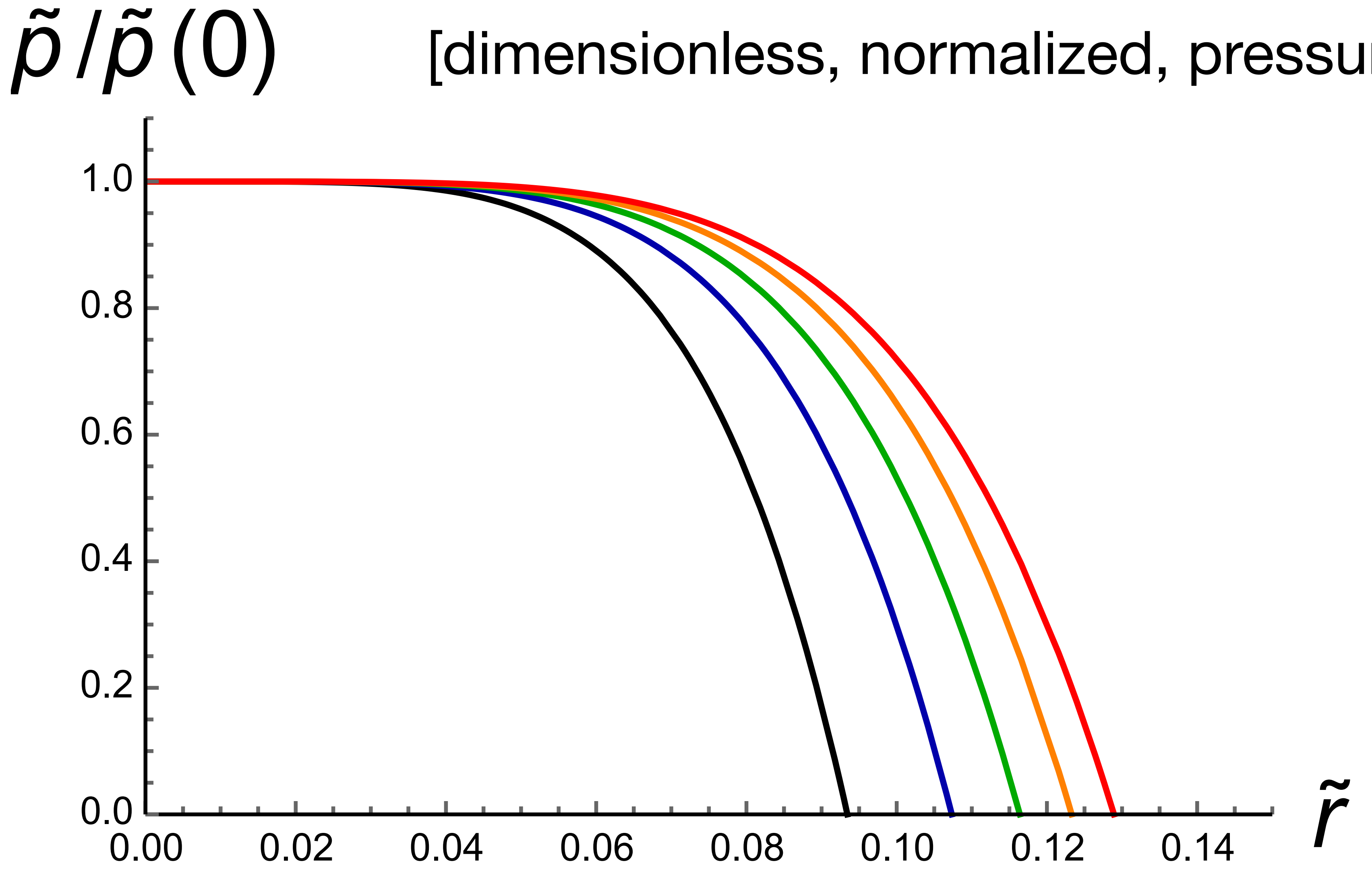
$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{G}{c^2}\frac{(p+\rho)(m+4\pi r^3 p/c^2)}{r^2[1-2Gm/(rc^2)]}$$

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2 \frac{\rho}{c^2},$$

Quark Matter Eq. Of State:

$$\Omega = -a_4\mu^4 + a_2\mu^2 + B_{\rm eff}$$

[Alford+ 0411016] $\frac{a_4}{a_2} \ll 1 \;\; , \;\; B_{\rm eff} \ll 1$



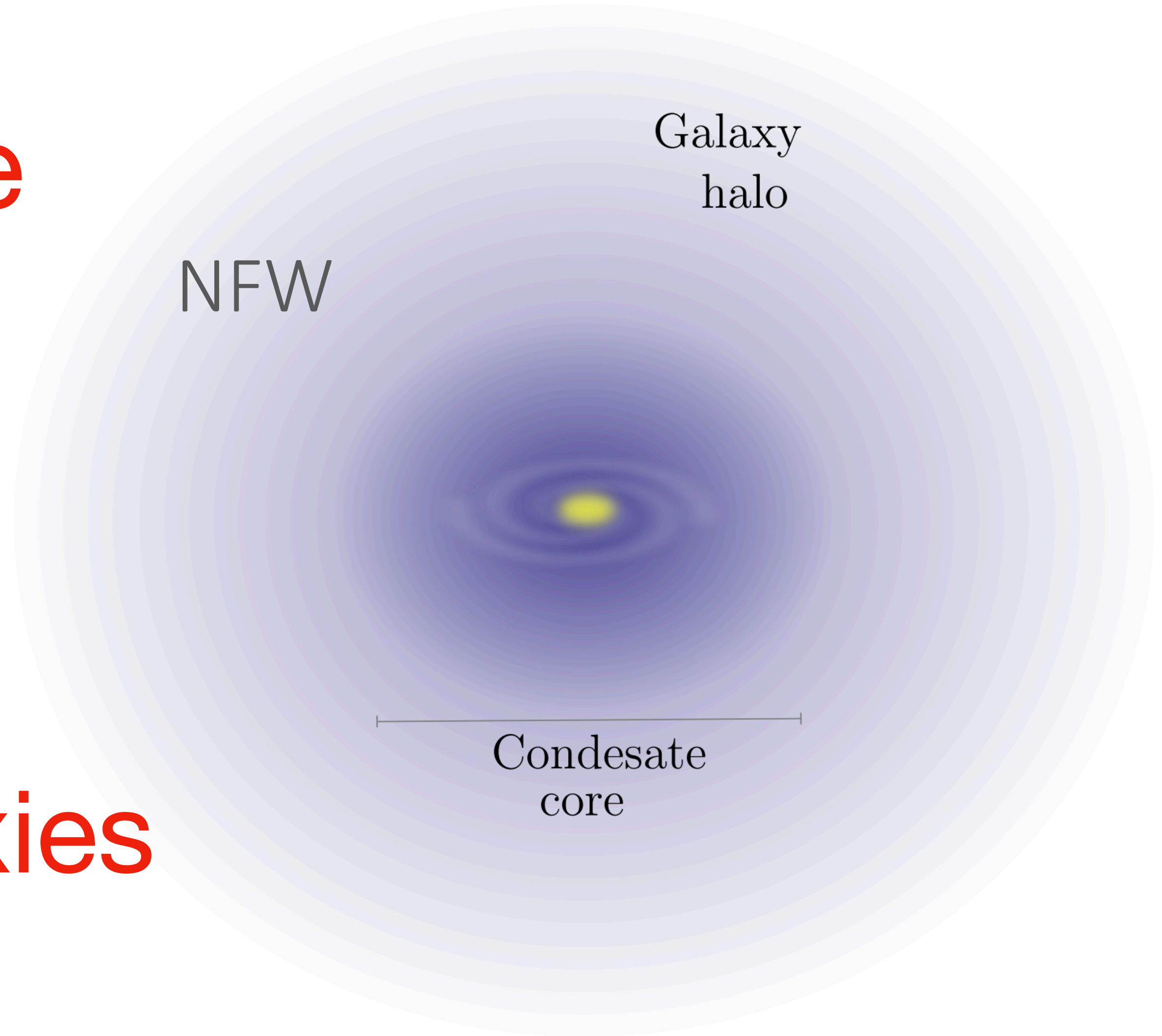
Constant Density Core

restore units:

$$\rho_0 \sim 5\times 10^8 M_\odot/\mathrm{kpc}^3 \quad , \quad r_c \simeq$$

In agreement with observations of dwarf galaxies

[e.g. Tucana: Gregory+ 1902.07228]



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Cooling

The dark baryons can emit a dark pion, dissipating energy

$$\mathcal{L}_{NN\pi} \simeq \alpha \frac{\partial_\mu \pi}{f_\pi} \bar{N} \gamma^\mu \gamma^5 N$$

R. Essig, S. D. Mcdermott, H.-B. Yu and Y.-M. Zhong, *Constraining Dissipative Dark Matter Self-Interactions*, *Phys. Rev. Lett.* **123** (2019) 121102 [1809.01144].

Cooling rate:

$$C = \rho^2 \frac{\sigma_{\rm diss.}}{m_{\rm DM}} \frac{4\nu\nu_{\rm loss}^2}{\sqrt{\pi}} \left(1 + \frac{\nu_{\rm loss}^2}{\nu^2}\right) e^{-\frac{\nu_{\rm loss}^2}{\nu^2}}$$

$$\nu_{\rm loss} \equiv \sqrt{\frac{E_{\rm loss}}{m_{\rm DM}}} \simeq \sqrt{\frac{m_\pi}{m_{\rm DM}}} c = \left(\frac{m_q}{\Lambda_{\rm QCD}}\right)^4 c.$$

Limits:

(1) Too much energy loss per collision: events too rare

(2) Too little: too little dissipation per event

In SIDM: Cooling can hasten gravothermal collapse

[STUMPs: expect no collapse (pressure of core)]

Limits for cooling to be negligible:

$$\frac{m_q}{\Lambda_{\rm QCD}} \neq [10^{-18}, 10^{-14}]$$

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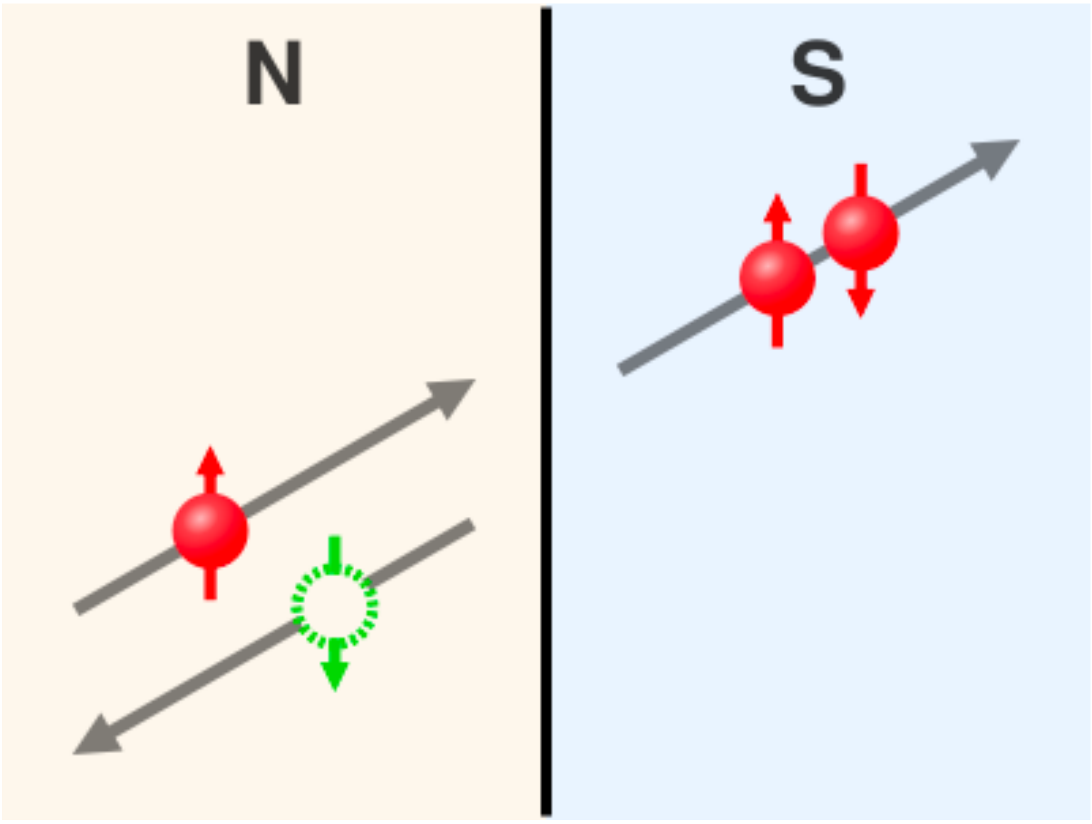
Dynamical Friction & Andreev Reflection

Andreev Reflection
[Andreev, 1964]

Charged Particle With Incoming Momentum p

If $p > \Delta$:



M. Sadzikowski and M. Tachibana, *Andreev reflection in superconducting QCD*, *Acta Phys. Polon. B* **33** (2002) 4141 [hep-ph/0208037].

Y. Juzaki and M. Tachibana, *Andreev reflection at Hadron/Color superconductor interface*, *Acta Phys. Polon. B* **51** (2020) 1911 [2006.07096].

When a superconducting core falls into a hadronic halo, gets an anomalous friction. Force on the core is:

$$F \sim f_{\rm scat}\rho_{\rm halo}A_{\rm core}v_{\rm halo}^2$$

Time-scale:

$$t_{\rm drag} = \frac{v}{a} \sim \frac{\rho_{\rm nucl}}{f_{\rm scatt}\rho_{\rm halo}}t_{\rm crossing} > t_{\rm crossing}$$

Very small effect

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Milli-B-charged particles

1. Gauged $U(1)_B$

B gauged at high energies, approximate global symmetry at low energies

$$\mathcal{L} = |DS|^2 + \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \lambda_s(S^2 - v_s^2)^2 + \mathcal{L}_{\text{new fermions}}$$

Idea : scalar S with $B_S \in \mathbb{Z}$

[Duerr, Perez and Wise, PRL 2013]

Cancel electroweak anomalies

[Ma 2011.13887]

new fermion	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$(E^0, E^-)_L$	2	$-1/2$	B_f
$(E^0, E^-)_R$	2	$-1/2$	$B_f + 3$
X_R^-	1	-1	B_f
X_L^-	1	-1	$B_f + 3$
X_R^0	1	0	B_f
X_L^0	1	0	$B_f + 3$

2. Kinetic Coupling

Visible U(1) couples to dark U(1). Gives small visible charge to dark matter

[Holdom PLB 1986]

$$\mathcal{L}_{DM} = |D\Phi|^2 + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\chi}\not{D}\chi + \frac{1}{4}\lambda_\phi(\Phi^2 - v_\phi^2)^2$$

$$\mathcal{L}_{mix} = \frac{\epsilon}{2}B_{\mu\nu}F^{\mu\nu} \quad \Rightarrow B_\chi = \frac{\epsilon}{3}$$

Equation of State of dense (dark) quark matter

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$$\Omega = -a_4\mu^4 + a_2\mu^2 + B_{\rm eff}$$

[Alford et al. 0411016]

$$p = -\Omega \;,\; n = \frac{d\Omega}{d\mu} \;,\; \rho = \Omega + n\mu$$

$$\rightarrow \quad p[\rho] = \frac{1}{3}(\rho - 4B_{\rm eff}) + \frac{r_{2,4}^2}{12\pi^2}\left(-1 + \sqrt{1 + \frac{16\pi^2}{r_{2,4}^2}(\rho - B_{\rm eff})}\right)$$

$$r_{2,4} \equiv \frac{a_2}{\sqrt{a_4}}$$

$r_{2,4} \gg 1$: color superconductor
$r_{2,4} \ll 1$: non-interacting fermions

B-number Anomalies:

$$\mathcal{A}_1\left(SU(3)^2 \otimes U(1)_B\right),\ \mathcal{A}_2\left(SU(2)^2 \otimes U(1)_B\right),$$
$$\mathcal{A}_3\left(U(1)_Y^2 \otimes U(1)_B\right),\ \mathcal{A}_4\left(U(1)_Y \otimes U(1)_B^2\right),$$
$$\mathcal{A}_5\left(U(1)_B\right),\ \mathcal{A}_6\left(U(1)_B^3\right).$$

$$\mathcal{A}_2 = -\mathcal{A}_3 = 3/2$$

All others vanish

Modern Astrophysics vs Dark Matter

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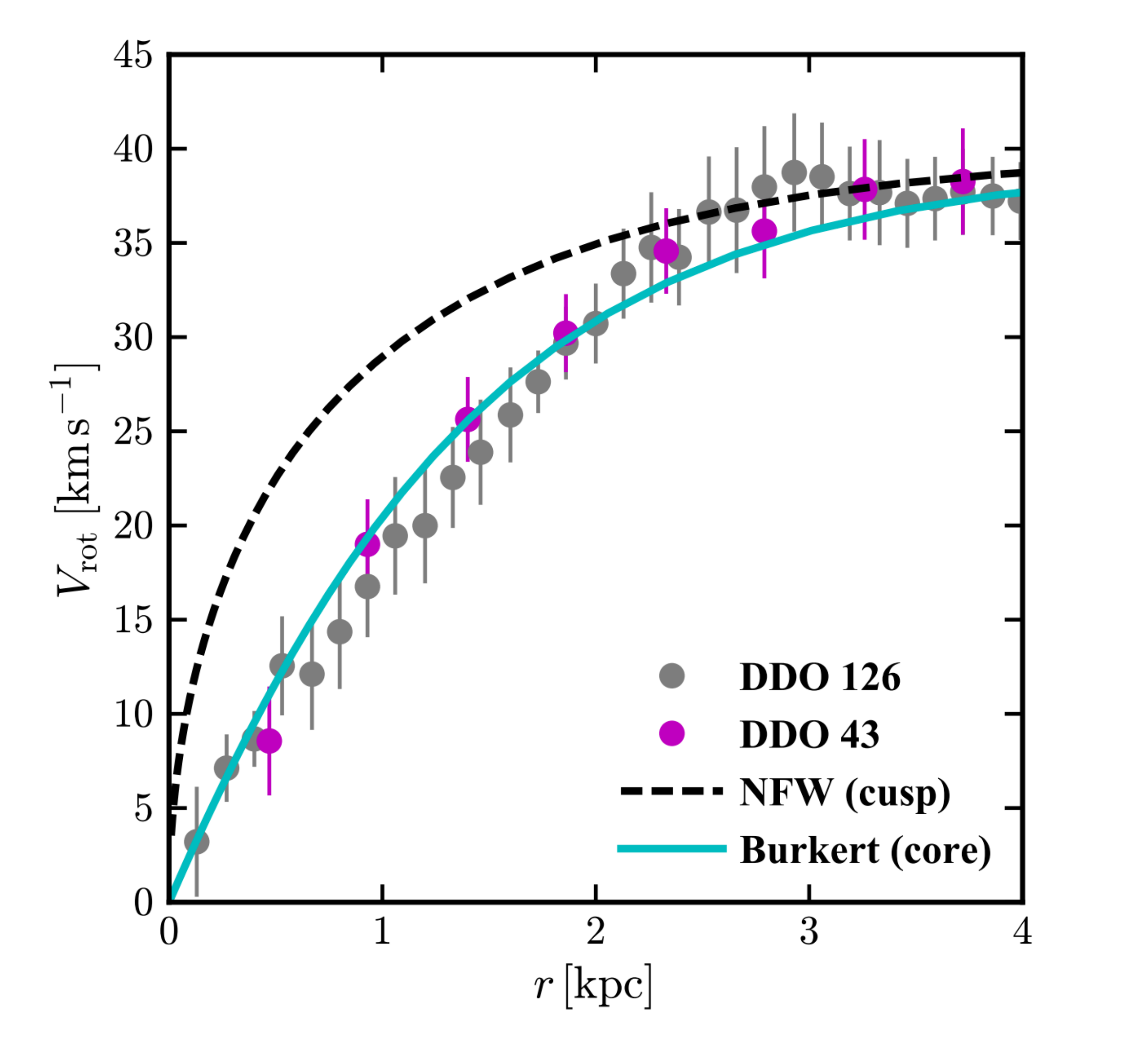
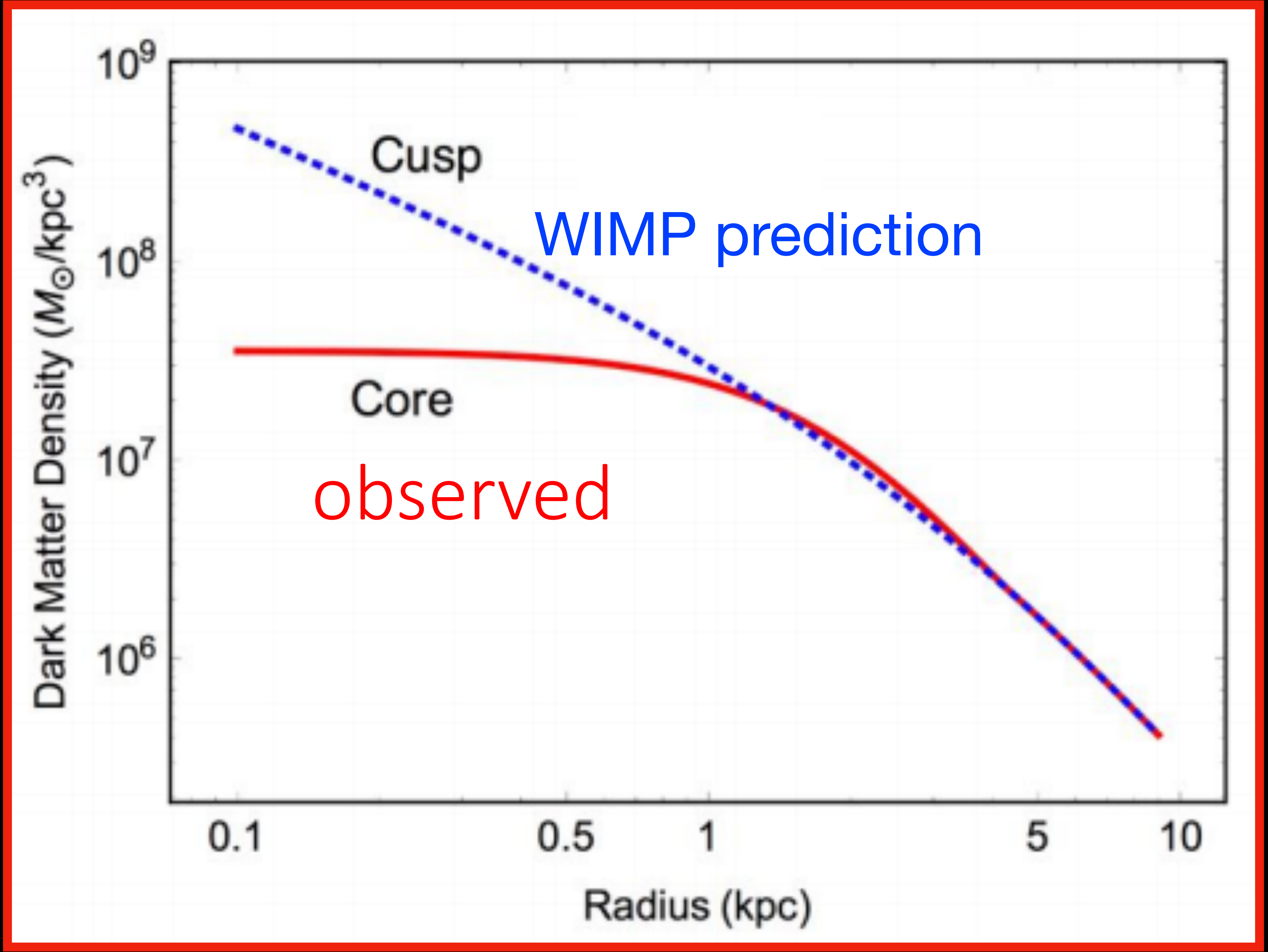
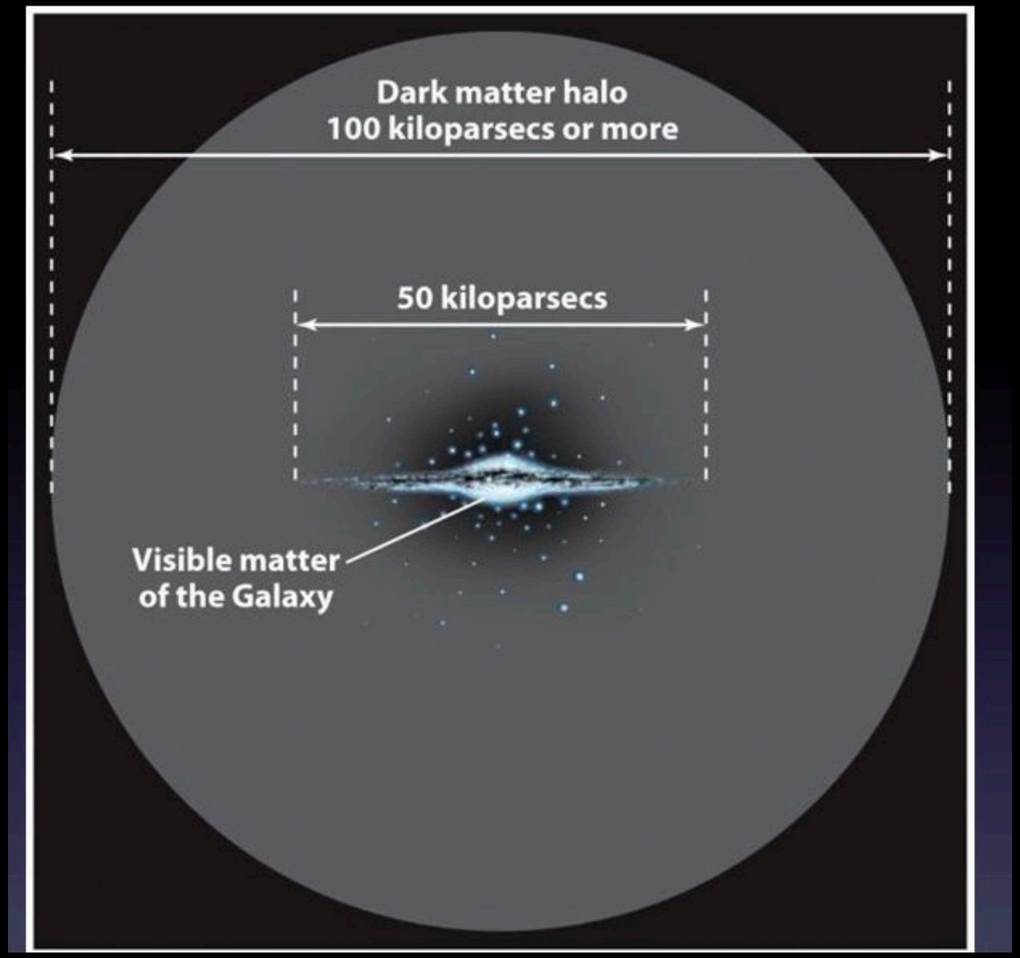
The Core-Cusp Problem

Data:
Rotation Curves







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II. Wave Particle Duality

Einstein

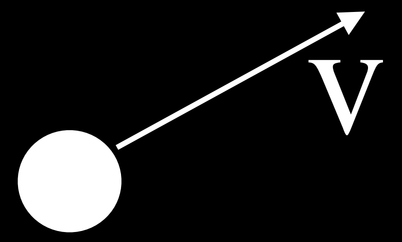
$$E = mc^2$$

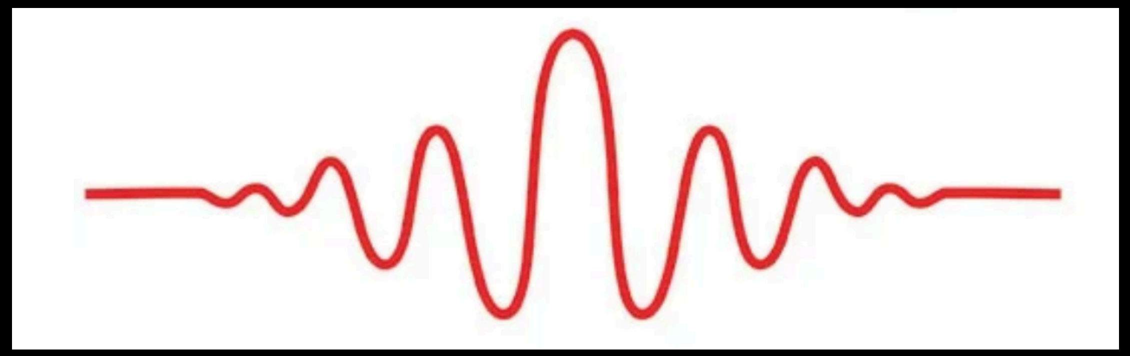
de Broglie

$$\longleftrightarrow$$

Planck

$$E = h\nu = \frac{hv}{\lambda}$$





Important for low-mass particles

For very high number density of particles, the de Broglie wavelengths can overlap

Dark Matter Wave Particle Duality in Action

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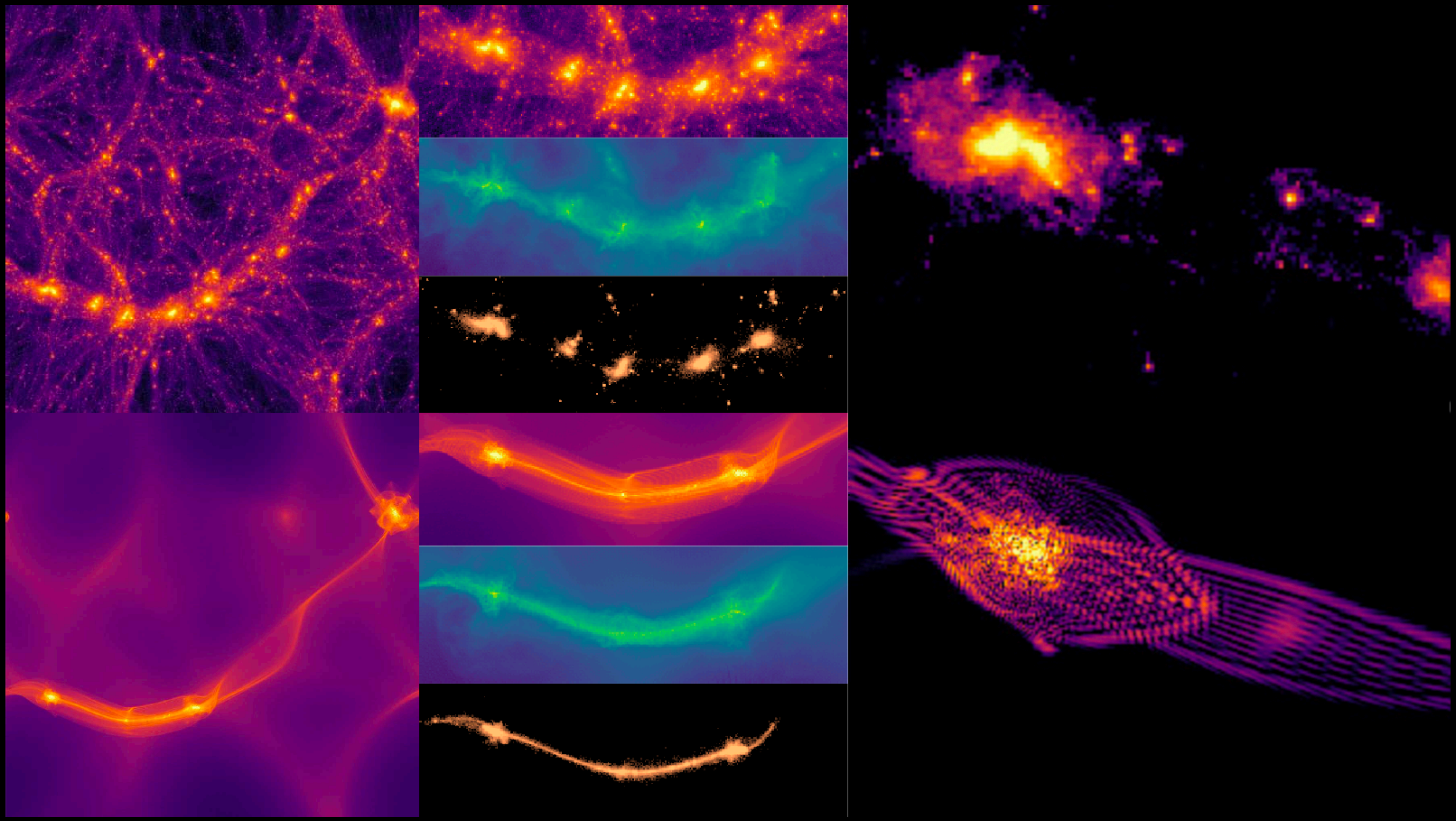

Image Credit:
Mocz et al.

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Question:

What is the quantum mechanical ground state of:

A huge number of bosons, at very low temperature

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Question:

What is the quantum mechanical ground state of:

A huge number of bosons, at very low temperature

Answer:

the bosons each occupy an identical quantum state.

The system behaves a single

macroscopic quantum system

Bose-Einstein Condensate

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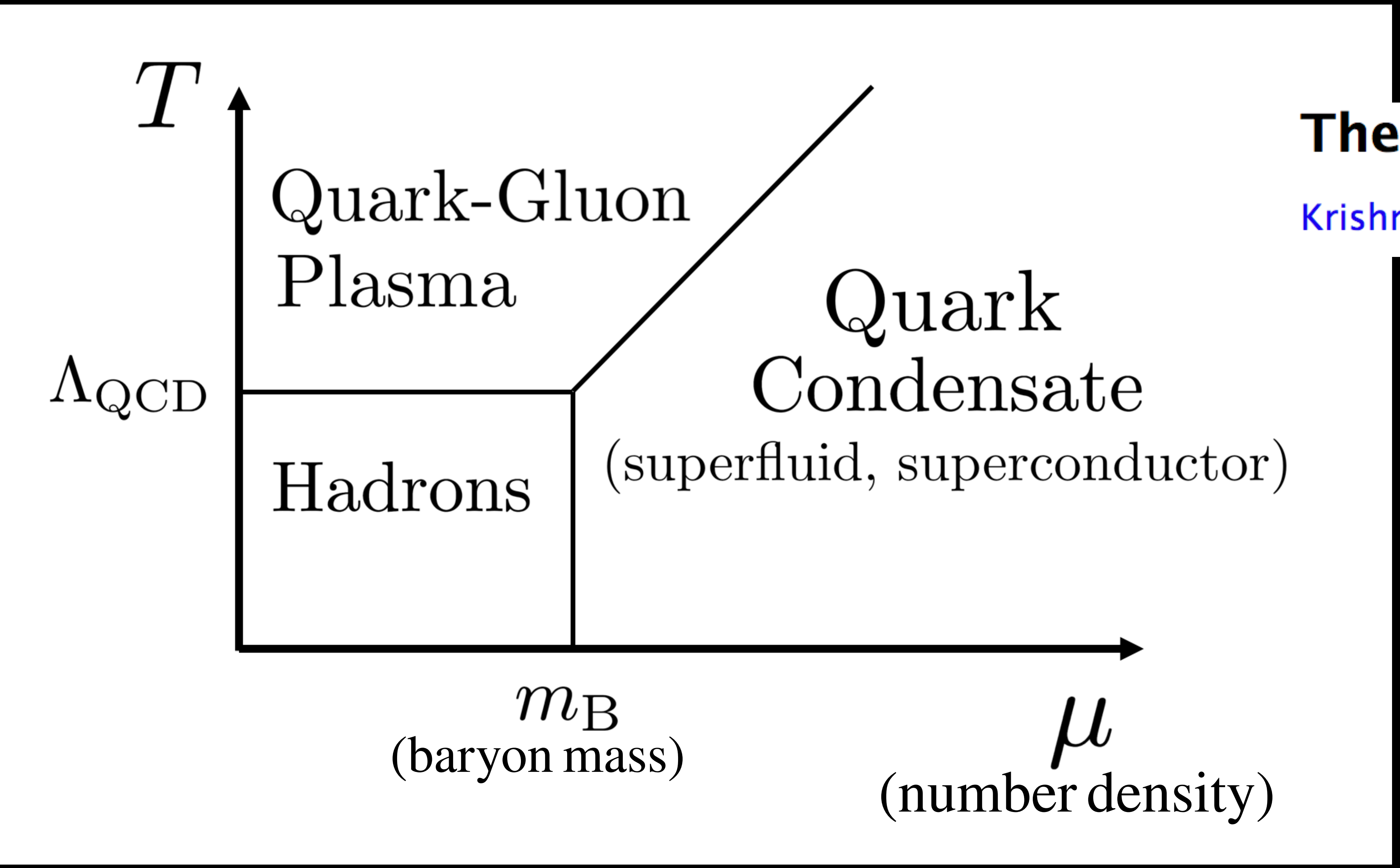
The Condensed Matters of Particle Physics

[EM, Spergel, Alexander arXiv:1801.07255]

[EM, Spergel, Alexander arXiv:2011.06589]

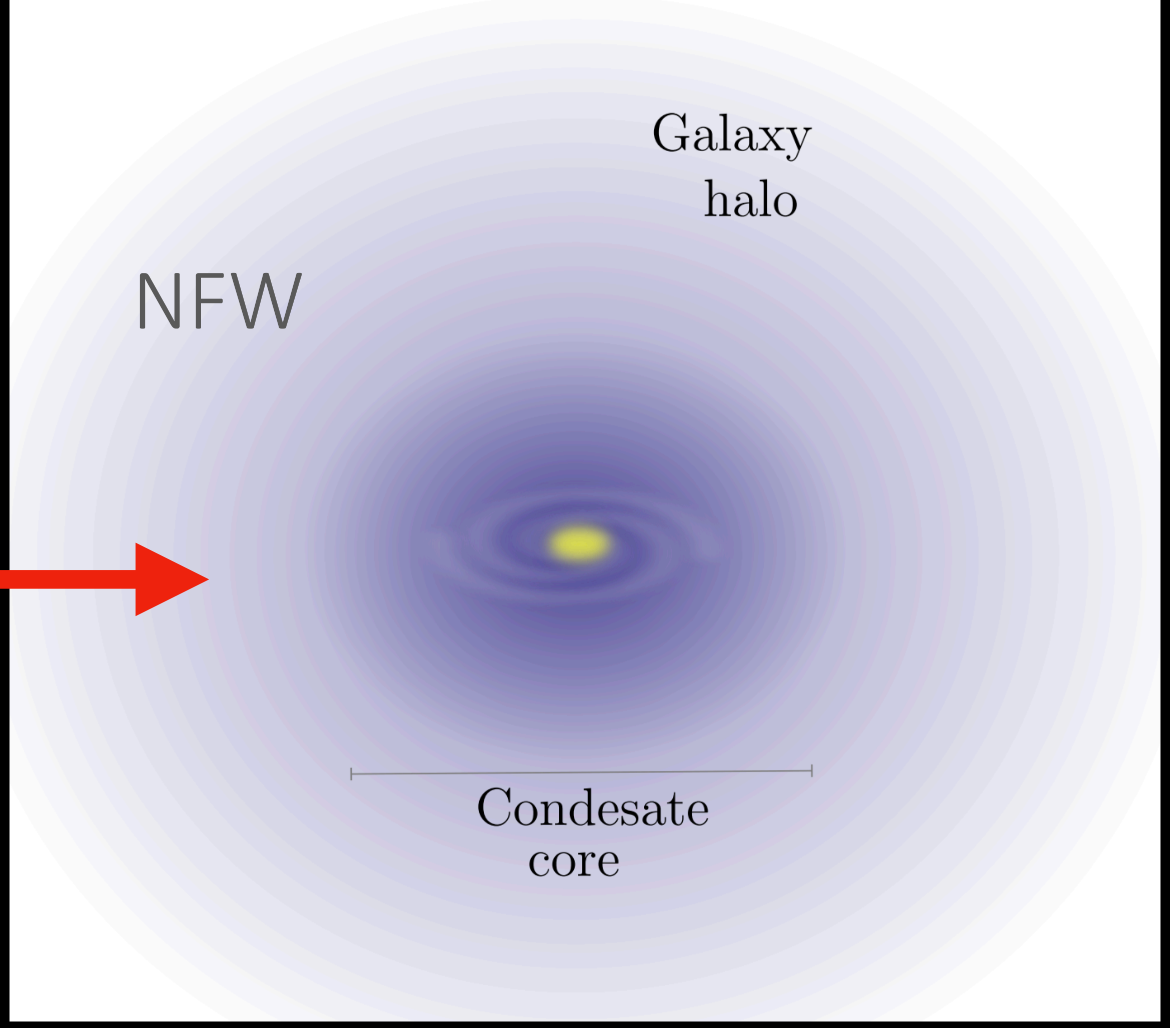
The Phase Diagram of Quantum Chromo-Dynamics



The Condensed Matter Physics of QCD
Krishna Rajagopal (MIT), Frank Wilczek (MIT)

What if "Nuclear Density" is cosmological?

$$m_{\rm dark-baryon} \sim 0.1 {\rm eV}$$



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Condensate Wave Function

Schrodinger-Poisson Equation

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + m\Phi\psi$$

+ self-interactions

$$\nabla^2\Phi = 4\pi G m|\psi|^2$$

Note: velocity of condensate = gradient of phase of wave function

Where to look for dark matter?

Astrophysics

Particle Physics

New ways of finding DM:

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1. Astrometry: Tracking the motions of stars in our own Milky Way [EM, Bramburger, Alexander arXiv:1901.03694]

2. Strong Gravitational Lensing by distant galaxies and galaxy clusters. Vortices! [EM, Toomey+ arXiv:1909.07346]

1. The Cosmic Web: Rotation of the largest structures in our universe, from vortices! [Capanneli, EM, Ferreira, Alexander arXiv:2111.03061]

New particle physics!

1. Why are we here? Connections to matter-antimatter asymmetry
2. Interactions with neutrinos: oscillating neutrino masses
3. Interactions with standard model quarks

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Astrometry:

Motions of stars trace of out the distribution of dark matter

Astrometry & Dark Condensates

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Fuzzy Dark Disk

[EM, Bramburger, Alexander arXiv:1901.03694]

$$\nabla^2 \psi = V\psi - \lambda |\psi|^2 \psi$$
$$\nabla^2 V = 4\pi G m |\psi|^2$$

Solve through "Far Field - Core Decomposition"
In a squeezed coordinate system

$$r_{\rm sq}^2 = \frac{1}{R^2}\left(x^2 + y^2 + (D-2)z^2\right)$$

$$\nabla^2 \equiv \frac{\partial^2}{\partial r_{\rm sq}^2} + \frac{D-1}{r_{\rm sq}}\frac{\partial}{\partial r_{\rm sq}} + \mathcal{O}\left(\frac{z^2}{D^2}\right)$$

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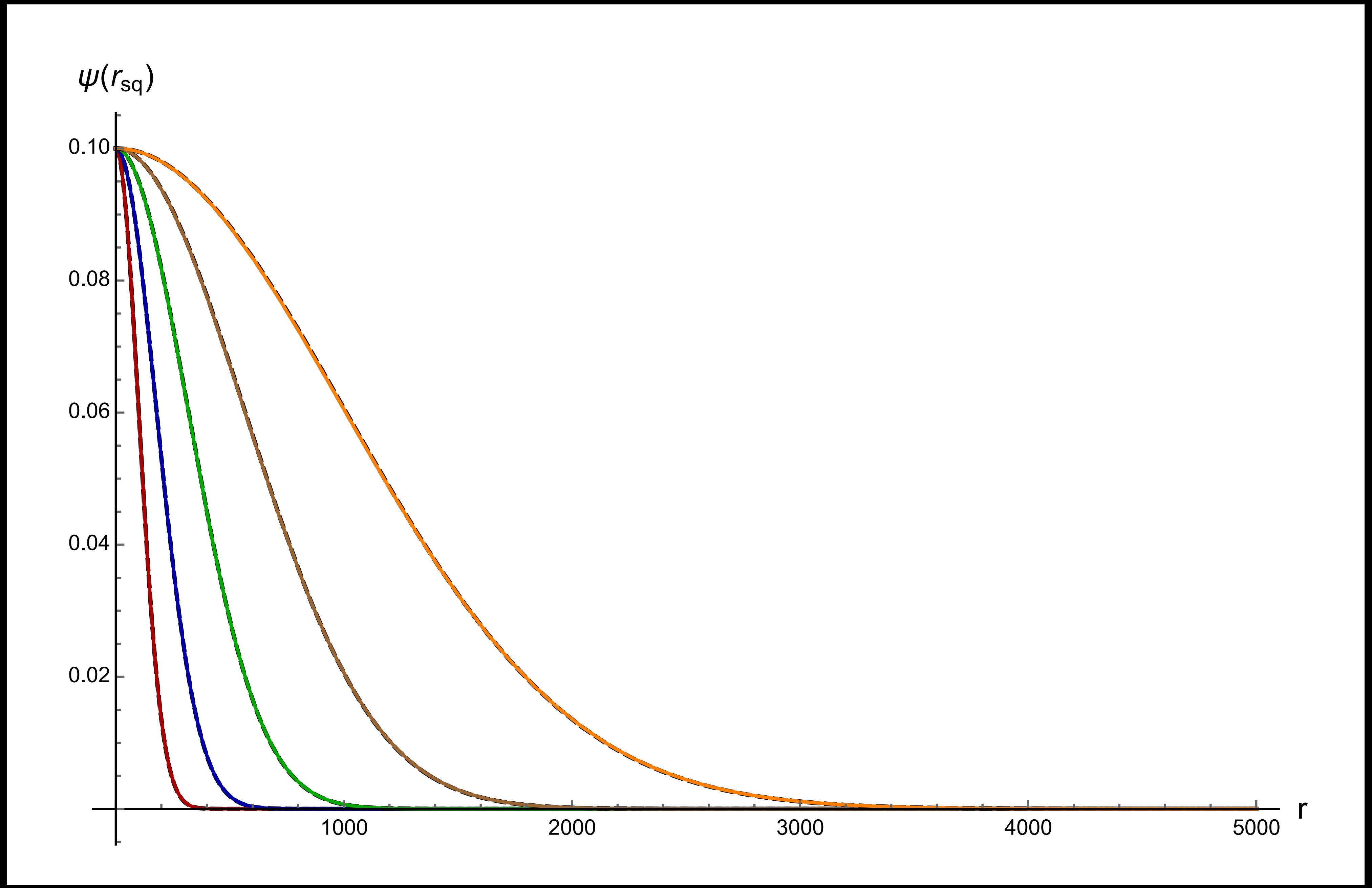
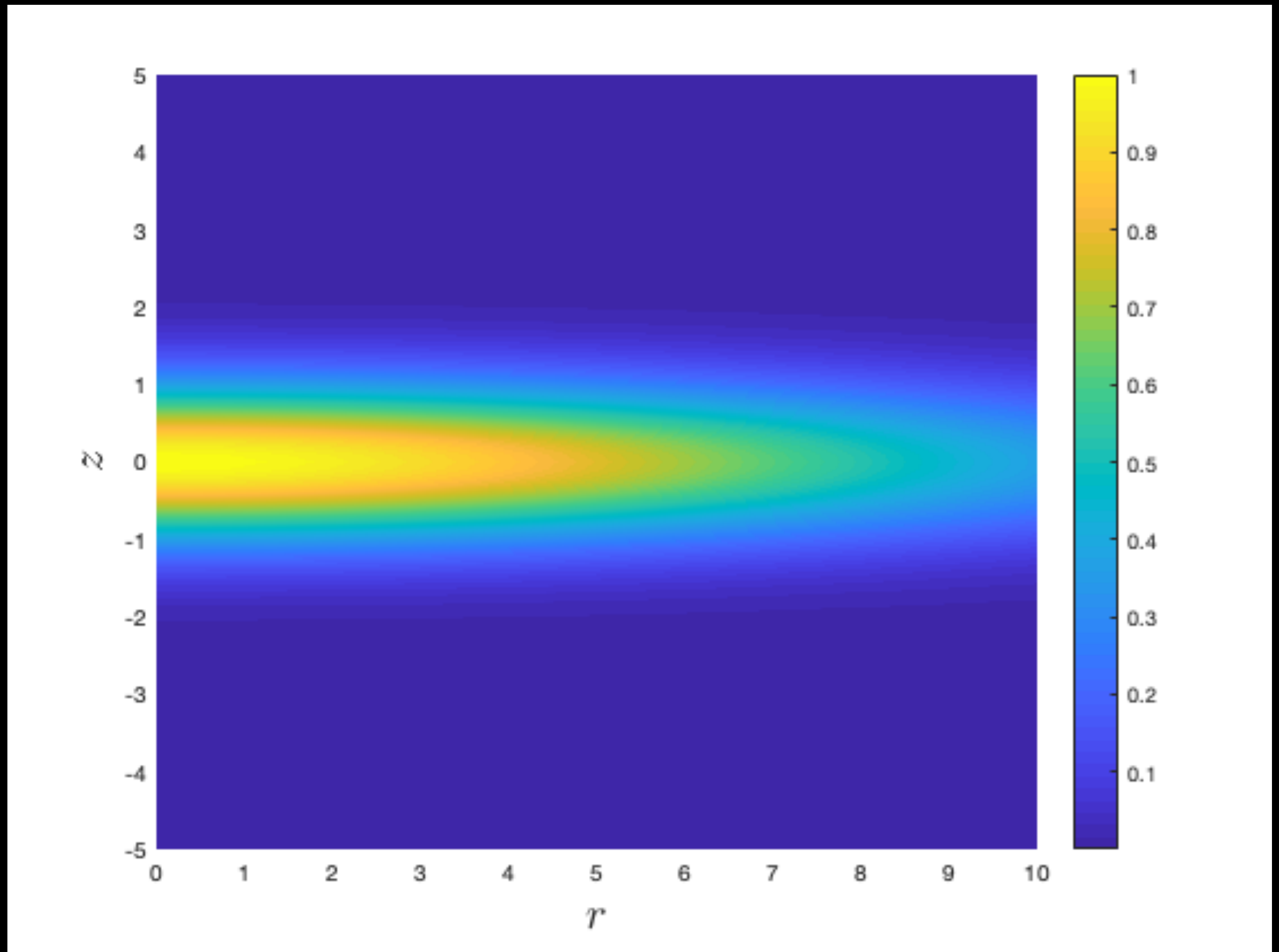
A Fuzzy Dark Disk

$$\nabla^2 \psi = V\psi - \lambda |\psi|^2 \psi \qquad \nabla^2 V = 4\pi G m |\psi|^2$$





Can constrain with the motion of stars!

[EM, Bramburger, Alexander arXiv:1901.03694]

The Cosmic Web

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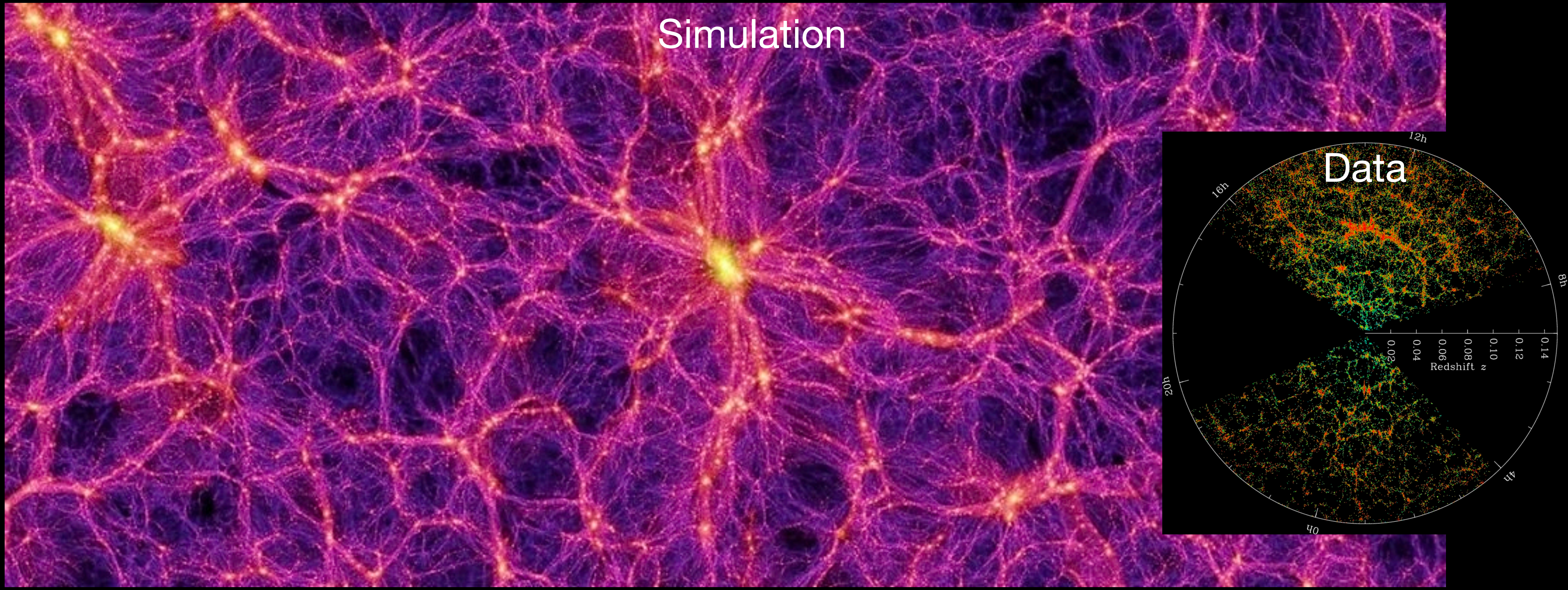

nature astronomy

ARTICLES

https://doi.org/10.1038/s41550-021-01380-6

Check for updates

Possible observational evidence for cosmic filament spin

Peng Wang[1], Noam I. Libeskind[1,2], Elmo Tempel[3], Xi Kang[4,5] and Quan Guo[6]

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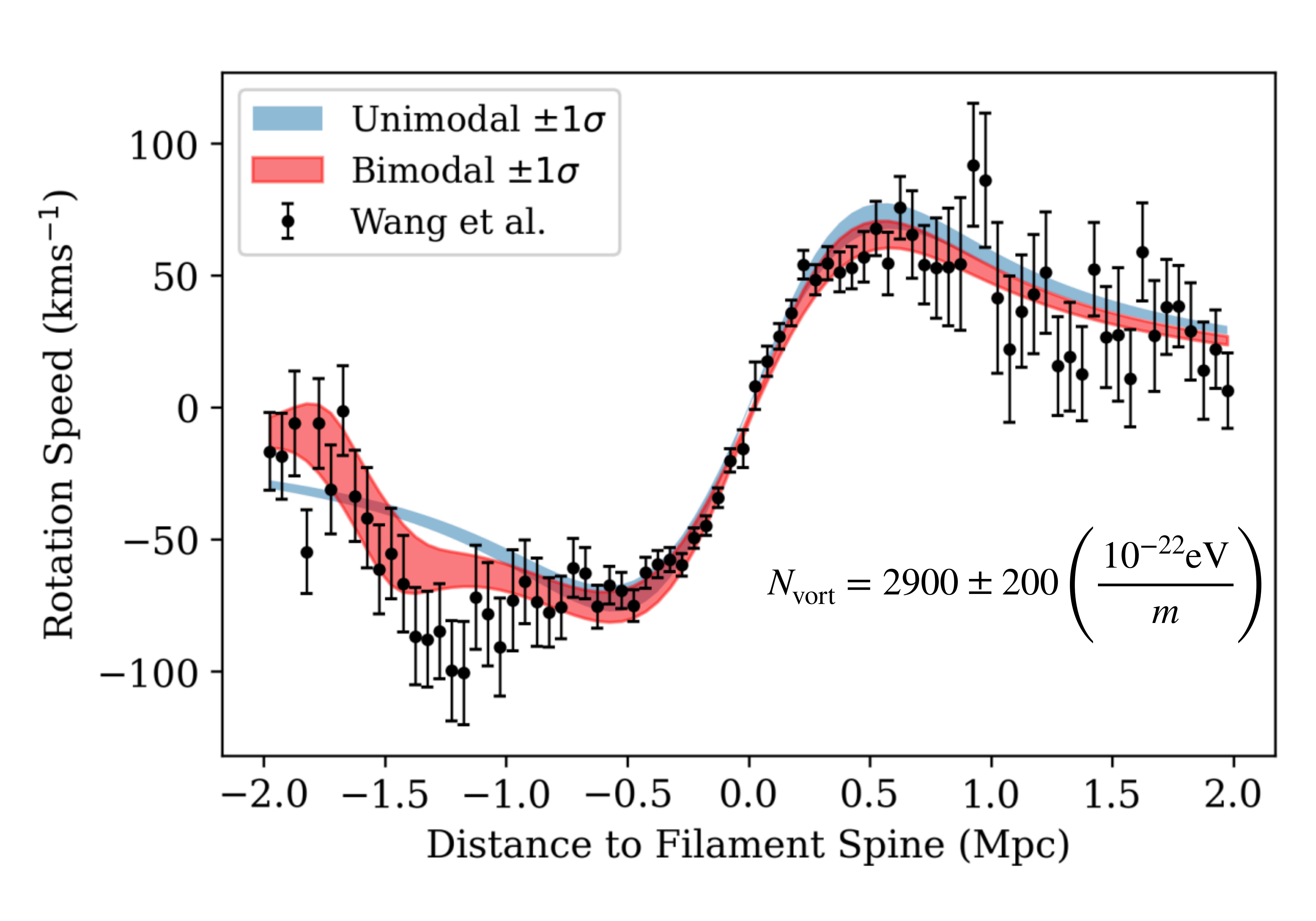
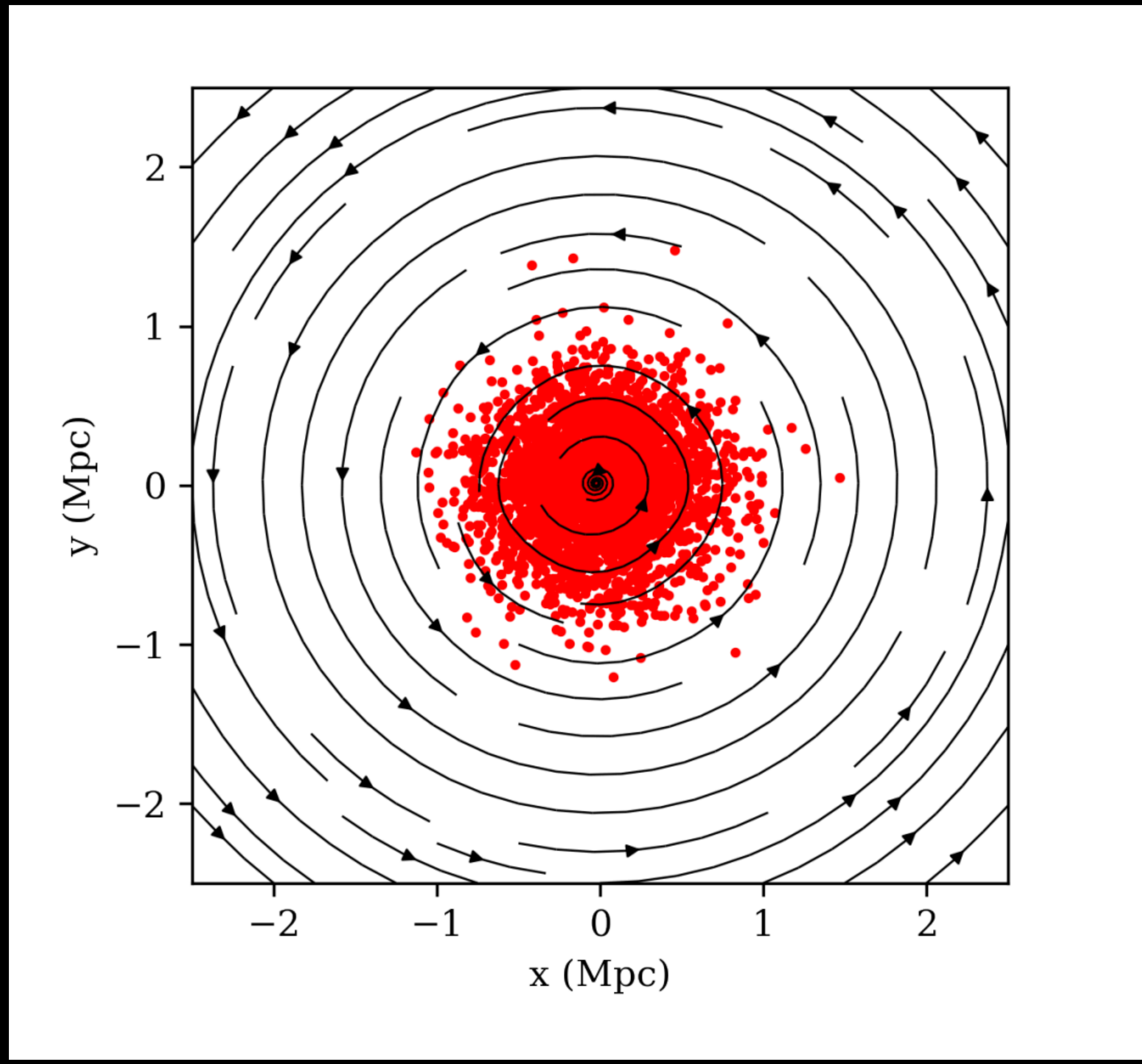
Spinning Cosmic Filaments from Dark Matter Vortices

[Capanneli, EM, Ferreira, Alexander
arXiv:2111.03061]



Example velocity field from a collection of vortices:
[vortex radius enlarged to be visible]



Summary

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What we know:

Dark Matter is definitely out there

What we don't know (*yet*):

What are the fundamental particles
that make up dark matter?

What we hope to learn soon:

The Nature of Dark Matter in astrophysical environments. The mass range and interactions of the dark matter particle

Thanks!

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Extra Slides